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Manufacturability Analysis of Metal Laser-based Powder Bed Fusion Additive Manufacturing -A Survey

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Abstract The laser-based powder bed fusion (LPBF) process is able to produce complex part geometries. The fast development of the LPBF process offers new opportunities for the industries. Most research done to date has focused on the modeling of the process, which shows that both part geometries and process parameters play an essential role in the result of end-product quality. The definition of the manufacturability of the LPBF is vague. In this review, the focus is set on the manufacturability of the metal-LPBF process. What manufacturability is in the LPBF process and how it is investigated so far are discussed. All process parameters and design constraints for LPBF processes are introduced. The relationship between process parameters and design constraints and how they affect the manufacturability are discussed as well. A detailed discussion on how other researchers evaluate manufacturability analysis of LPBF is conducted. Finally, the manufacturability of LPBF is defined, and future prospects on filling the research gaps on the manufacturability analysis of the LPBF are presented.

Keywords Manufacturability · Laser-based powder bed fusion · Additive manufacturing

1. Introduction and Background

Laser-based Powder Bed Fusion, referred to as LPBF is a type of Additive Manufacturing (AM) process. In the metal LPBF process, a laser beam as a power source will melt and fuse the metal powder according to the given pattern on each layer. After one layer is done, the next layer of metal powder will be applied, and the laser is projected. The process

continues layer by layer until the products are completely built [1-4]. The schematic of the LPBF process is shown in Fig. 1. The LPBF process is ultimately about the successful control of heat transferred from an intense laser beam to a powder bed with poor heat conductivity to produce the geometrically precise localized fusion of powder [5]. The fusion mechanisms can be grouped into four groups, which are solid-state sintering, chemically induced binding, liquid-phase sintering (LPS), and full melting [6]. When metal is used, LPS and full melting are two conventional approaches to solidify metal powder.

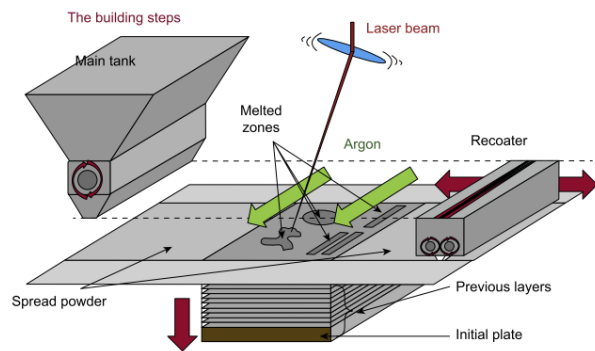


Fig. 1 Schematic of the LPBF [2]

Because of its relatively high resolution, numerous material choices, and potentials on manufacturing virtually any shape, the process is widely used and studied in both academics and industries [4, 7-9]. The application of LPBF can be found in medical and dental, aerospace, automotive, energy, and tooling industries [7, 9-14]. Compared to Conventional Manufacturing (CM), the LPBF process is more suitable for prototyping and low

production volumes of high complexity parts due to its advantages on the cost, production time, and machinability [8]. Opposite to subtractive manufacturing methodologies, it provides more design freedom with the layer upon layer material addition approach [4]. As no tooling is needed in the LPBF process, designers could consider more complex geometries that are not achievable by CM processes. The growing market demand on the LPBF process boosts increasing research efforts in academia [7, 15, 16].

Over the past twenty years, significant research has been carried out in the field of LPBF. Process, materials, designs, applications, and constraints related to LPBF have been investigated extensively and summarized in a recent survey paper [17]. With the rapid iterative deployment of LPBF equipment, the process is updated and improved to become mature. More and more materials became available for LPBF processes such as Aluminium AlSi10Mg, Cobalt Chrome MP1, Maraging Steel MS1, Nickel Alloy HX, Stainless Steel 17-4PH, Titanium Ti64ELI, Tungsten W1, etc. [18] With the expansion of materials and equipment, industries try to employ LPBF to benefit their current design or manufacturing process in various applications. More recently, the LPBF process started to fabricate functional end products, not just prototypes anymore. However, at the current stage, the LPBF process still has a very high threshold for users to take the full advantage of its capabilities in fabricating complex parts. It has a large number of selections on materials, machines, and parameter settings. It requires designers to have extensive knowledge of the LPBF process in order to make the design manufacturable. Even for an advanced commercial LPBF machine, printing can fail due to many factors such as build orientations, support structures, minimum features, and so on. Furthermore, even after the objects are printed “successfully”, it may not qualify the design requirements such as mechanical properties. The term “manufacturability” needs to be re-defined for the LPBF process. It was

shown that the qualities of the final product such as dimensional accuracy, surface finish, and mechanical properties are related to many factors such as process plans with a sequence of operations and values of process variables, and design structure with information about the geometric of a design and materials used in production [19].

The study on the manufacturability of the CM process can be traced back to World War II [20] due to the political pressure to build better weapons. After that, increasing global competition and desire to reduce the time and cost led to the increasing awareness of the manufacturing consideration [21]. Many approaches and studies were proposed to analyze the manufacturability of the CM process in the past. There are also a certain number of good survey paper to summarize the existing approaches. On the other hand, for the AM process, especially for the LPBF process, many researchers have studied the design rules for LPBF [22-27]. They focused on finding the constraints on designs such as minimum thickness, overhangs, holes, channels, build orientation optimizations, etc. The design features that exceed these constraints may cause failure during fabrication. For example, a 10-cm long overhang typically cannot be fabricated by the LPBF process horizontally but could be printed vertically. Another approach to investigate the manufacturability of the LPBF process is to understand the influence of process parameters such as laser power, scanning speed, particle size, layer thickness on the qualities of the fabricated objects [28-43]. However, as the design constraints and process influence are closely coupled, neither of the aforementioned manufacturability investigation approaches is able to cover the topic comprehensively. The design constraints investigated without considering process influences are not fully applicable when key process parameters are changed and vice versa. Moreover, there is no critical literature review on the manufacturability analysis of the LPBF process.

Hence, in this paper, as a maturing manufacturing process, the existing approach to evaluating the manufacturability of CM will be introduced in Section 2 first as the background on how researchers evaluate the manufacturability in the past. Section 3 and 4 will review and discuss the recent research related to the manufacturability of the LPBF process. Based on the review of the literature, a new definition of the manufacturability of the LPBF process and the keys of the manufacturability analysis will be proposed in Section 5. Discussion and comparison of the current works in literature are conducted in Section 6. The paper ends with conclusions and some prospects. The purpose of this article is to provide a comprehensive review of how the manufacturability of LPBF is modeled in the literature. It states the research gaps in the existing studies and offers the future direction of the research in the manufacturability analysis of the LPBF process.

2. Existing Approach on Evaluating the Manufacturability of CM

In the past, the manufacturability analysis was always conducted by the designer. Designers use their experience to evaluate the manufacturability of their design. There are some guidebooks published by the leading professional societies or the manufacturers to provide all design rules based on the particular manufacturing process. Designers should read carefully through these heavy guidebooks to avoid those configurations, which may result in poor manufacturability. The quality of the manufacturability analysis is also highly dependent on their working experience. In order to help designers on the manufacturability evaluations, the automated manufacturability analysis is developed. After years of research and development, manufacturability analysis has become an essential part of CAD/CAM systems. Commercialized software such as DFMXpress in Solidworks, VAYO, DFMPPro, etc. have been released for users to evaluate the manufacturability. The

manufacturability of CM can be defined as four characteristics: visibility, reachability, accessibility and setup complexity [44]. Studies with different approaches to evaluate the manufacturability of the selected CM process have been published as well [21, 45-49]. According to the existing literature reviews, the main strategies for those approaches can be classified as two groups based on the geometric interpretation: feature-based approach and feature-less based approach [44, 49, 50]. In this review, since most manufacturability analysis of the CM process focuses on the Computer Numerical Control (CNC) machining, it is chosen as the representative to describe CM. Even for the injection molding, the manufacturability analysis is focused on determining whether the mold is manufacturable or not, and the mold is always fabricated by CNC machining. Therefore, the following discussion is restricted to the CNC machining process.

2.1. Definition of the manufacturability of CM

Given the design and a selected CM process, the definition of the manufacturability in CM is straightforward. It is defined as whether or not the design is manufacturable in shape, dimensions, tolerances, and surface finishes. The design or features are evaluated on the manufacturability with respect to four characteristics: visibility, reachability, accessibility and setup complexity [44]. Fig. 2 provides a geometric explanation for each characteristic. Visibility depicts the view from the machine tool to the part. A part has high visibility if the surface area of the entire model can be seen from the view of the machine tool. Reachability stands for the lengths required for the machine tools to reach the surface of the model. The shorter length of the machine tool is preferred. Accessibility measures the ability of a model to be machined without tool collisions. Accessibility is found to be dependent on both the surface geometry and the tool size. Setup complexity measures the number of setups required to fabricate a part. When machining a complex geometry, the tool may need to be rotated in order to

access certain features. In the existing research works, accessibility is the most popular evaluation

criteria on both the feature-based approach and feature-less based approach.

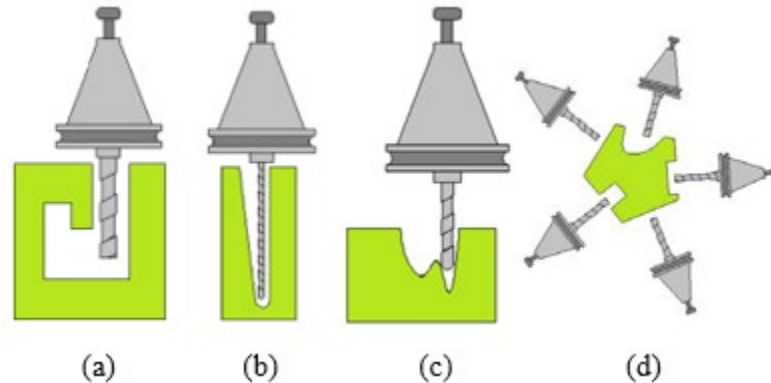


Fig. 2 Geometric explanation for machining characteristic (a) Visibility, (b) Reachability, (c) Accessibility, (d) Setup Complexity [44]

2.2. Feature-based Approach

The general idea of the feature-based approach is to extract the machining features such as holes, rockets, or machinable surfaces from the design features. Those extracted features will then be used as the input of the manufacturability analysis. The feature-based approach can be further distributed into three most active approaches according to Han's review [49]: graph-based approach, volumetric decomposition approach, and hint-based approach. The graph-based approach determines the feature types by translating the given design into multiple graph patterns. The part graphs will be analyzed to determine the features [51]. This approach has been successful in recognizing some types of features but has some difficulties when faces are altered due to feature intersections. For the volumetric decomposition approach [52], the general idea is to decompose the geometric input into volumes and interpret volumes to the machining features. The decomposition operation can be either convex hull decomposition [53, 54] or cell-based decomposition [55, 56]. The convex hull deposition is based on the geometric boolean operations, and the cell-based deposition asked to decompose the volume into the cells, and then composed to generate a volume to a machining feature. The issue in the volumetric

decomposition approach is that the result features may not match with any predefined feature types after the decomposition. The hint-based approach determines the machining features by following the defined rule which asserts a feature and its associated operation. The most recognized hint-based reasoning algorithms were proposed by Regli for F-Rex [57], Han for integrated incremental feature finder [58], Brooks for feature-based machining husk system [59], and Vandenbrande for object-oriented feature finder [60]. The major issue in the hint-based approach is that it is difficult to interpret all the machining features.

2.3. Feature-less based Approach

The feature-based approach mainly focuses on detecting manufacturable features on the selected machining process. On the other hand, the feature-less approach analyzes the surface representation of the model to determine the manufacturability. It ideally works with any arbitrary geometries without feature recognition [44]. Moreover, in the feature-based approach, most approach comprises all the geometric elements as an entity to be a machining feature. However, this actually constrains the manufacturability analysis. For instance, for multi-axis machining, it is possible to fabricate a portion

of the feature in one direction and then finish the remaining portion after changing the tool setup orientation. The feature-less approach can solve those issues which are difficult to solve using the feature-based approach. Li proposed the feature-less based strategy to determine the manufacturability of a part by slicing geometry files to map machinable ranges [50]. The slices are taken orthogonal to the axis of the rotation. The accessibility is estimated by the visibility of the light line on the 2D slice file. Machining simulation proposed by Jang offers another direction by using the voxel representation in generating collision-free tool paths and determining cutting parameters to increase the fabrication success rate. Kerbrat [45] presented a more advanced approach by decomposing the geometric model into octrees and evaluate the manufacturability index on each octant (an example shown in Fig. 3). Compared to the voxel-based and slice-based feature-less approach, the octree-based approach can acquire high accuracy relatively quickly. His approach also offers the potential for evaluating manufacturability on the consideration of both machining and additive manufacturing.

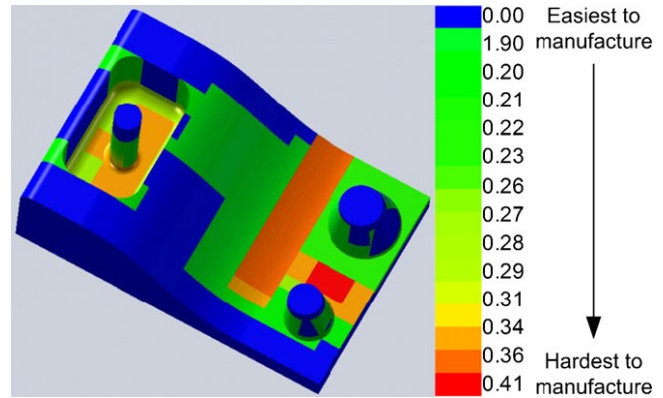


Fig. 3 Map of manufacturing difficulties and the associated color scale [45]

3. Existing approach on evaluating the manufacturability of LPBF

Efforts on manufacturability analysis of the LPBF process are conducted by a few researchers. To summarize the studies done in the literature, the recent efforts to evaluate the manufacturability of LPBF are categorized into three groups (Table 1): design guidelines/checklists, real-time process monitoring, and computational method in manufacturability analysis. A large number of studies have been carried out in the real-time process monitoring in LPBF. In this section, the definition of the manufacturability of LPBF will be introduced first, and the exiting non-computational approaches in evaluating the manufacturability are summarized and discussed. The existing computational approach will be fully explained and discussed in the next section.

Table 1 Major approaches in the literature on modeling the manufacturability

Approaches		Description	Reference
Design guidelines/checklists		Numerous experiments were done to provide a manufacturable range of geometric design features, including minimum thickness, part orientation, surface roughness, chamfers and radius, holes, overhang, etc. Designers are expected to follow those guidelines or checklist in their design.	[23, 24, 26, 27, 61, 62]
Real-time process monitoring		Using image-based real-time monitoring to detect and predict potential failure and printing quality during the process.	[63-77]
Computational methods in manufacturability analysis	Manufacturing features recognition	Automate the identification of erroneous features that are under the capability of the selected printer. The general idea of this approach is to discretize the 3D model into 2D/2.5D segments to reduce the difficulty of direct identification of 3D features. According to the types of input data for feature recognition, prior research can be classified as 3D feature-based approach, slicing data-based approach, voxel-based approach, and others.	[78-89]
	Integrated modeling	Integrate the models of design aspects and the material and process aspects to predict the performances of the AM parts	[90, 91]

3.1. Definition of the manufacturability of LPBF

The definition of the manufacturability of LPBF is vague in the literature. For the CM process, the product is fabricating by removing the materials from the solid blocks. Hence, the products from the CM process are always considered to be dense. The only consideration is the geometric inconsistency. However, for the LPBF process, the metal parts are built from powders layer by layer. The density of the part varies. As investigated in the literature, the mechanical and microstructural properties of specimens fabricated via the LPBF process may vary due to the different building orientations or different process parameters [92]. In the past, investigations of simulations, modeling, materials, and design optimizations of the LPBF process have been conducted extensively. However, gaps still largely exist in understanding and representing manufacturability. Designers are challenged with the lack of understanding of LPBF capabilities and

the influence of process parameters on the final products [62]. When considering the manufacturability of the LPBF process, two questions must be answered. The first question is whether the part can be successfully fabricated or not, meaning if all the geometry can be successfully built without considering their dimensional and geometric accuracy. Not all geometric features can be fabricated in LPBF. Many features present printing difficulties such as inclined surface, overhangs, holes, walls, et al. Fig. 4a gives an example of incomplete printing. The bottom area of the objects failed to be fabricated in this case due to the improper support structure added to the bottom. Designers may think the certain geometry is not printable through LPBF; however, Fig. 4b shows a similar geometry printed from another printing direction using a different machine. Compared to Fig. 4a, the lattice part in Fig. 4b has been successfully printed, but the flat top cover is warped

and not completely printed. All of that highlighted area is considered to be not manufacturable. It is hard for designers who are not experts in LPBF to determine those potential failures at the early design stage. The second question is whether the fabricated parts are satisfactory to customers' requirements in terms of dimensional accuracy, geometric accuracy, and mechanical properties. Those technical requirements are the standards to determine whether the final products meet the required qualities or not [93-95]. For the LPBF process, the technical requirements can vary based on different applications. In addition, for most studies in the literature, researchers majorly consider the geometric inconsistencies for the manufacturability analysis of the LPBF process like what they did in the manufacturability analysis of the CM process. However, as discussed above, it apparently shows that only considering the geometric aspects may not be sufficient for the manufacturability analysis. A clear definition of the manufacturability of the LPBF process is critically needed. A new definition of the manufacturability of the LPBF process will be introduced later in Section 5.

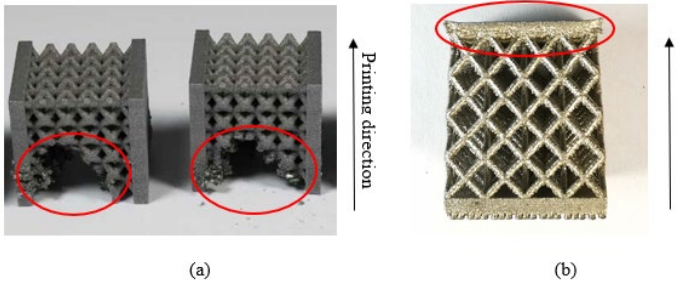


Fig. 4 Examples of unsatisfied printing

3.2. Design Guidelines/Checklists

In order to bridge design to real manufacturing, how to model the manufacturability or manufacturing capabilities is the question both academics and industries want to answer. Both industries and academics have conducted research to represent manufacturability in the form of design guidelines for different AM processes including the LPBF process [27, 96, 97]. Numerous experiments were

done to provide a manufacturable range of geometric design features including minimum thickness, part orientation, surface roughness, chamfers and radius, holes, overhang, etc. Designers are expected to follow those guidelines in their design. However, most of the design guidelines for the LPBF process only focus on the limitations of a single standard design feature, while high complexity design that is specialized by the LPBF process to produce is rarely studied [98]. Also, most of the guidelines assume the users have prior knowledge and design experience with the LPBF process. It is not the case for novice users.

Booth's group presented another approach, which is called the design for additive manufacturing worksheet [27]. A worksheet (Fig. 5) is provided as a checklist for the designer to prior validate whether their design is manufacturable or not. For each category, the importance of weight will be applied, and the final total score is calculated. The score is grouped into levels of manufacturability. It offered a simple visual list of details that addresses common mistakes in the AM process. Designers can evaluate how well their designs suit the LPBF process based on that checklist. The worksheet approach can provide an initial evaluation of the design, but it may not work for complex designs because the worksheet simplifies the entire design guidelines by offering the most common suggestions. The issue in both guidelines and worksheet approaches is that they only consider the design aspects. Each printer has some unique characteristics. By varying process parameters, some of the challenging geometric features may still be successfully made. Such examples were fully demonstrated in the literature where process parameter optimization is conducted to improve manufacturability [1, 32, 99, 100].

Design for Additive Manufacturing

A quick method for reducing the number of printing and prototyping failures, by Joran Booth
 Introduction: Mark one for each category for the part you plan to print. Check daggers and stars first, then scores

Complexity	Functionality	Material Removal	Unsupported Features	Sum Across Rows	Totals
Mark One Simple parts are sufficient for AM <input type="radio"/> The part is the same shape as common stock materials, or is completely 2D <input type="radio"/> The part is mostly 2D and can be made in a mill or lathe without repositioning it in the clamp <input type="radio"/> The part can be made in a mill or lathe, but only after repositioning it in the clamp at least once <input type="radio"/> The part curvature is a complex (spines or arcs) for a machining operation such as a mill or lathe <input type="radio"/> There are interior features or surface curvature is too complex to be machined	Mark One Add parts are light and medium duty <input type="radio"/> Making surfaces are bearing surfaces, or are expected to endure for 1000+ of cycles <input type="radio"/> Making surfaces move significantly, experience large forces, or must endure 100-1000 cycles <input type="radio"/> Making surfaces move somewhat, experience moderate forces, or are expected to last 10-100 cycles <input type="radio"/> Making surfaces will move minimally, experience low forces, or are intended to endure 2-10 cycles <input type="radio"/> Surfaces are purely non-functional or experience virtually no cycles	Mark One Support structures are surface finish <input type="radio"/> The part is smaller than or the same size as the required support structure <input type="radio"/> There are small gaps that will require support structures <input type="radio"/> Internal cavities, channels, or holes do not have openings for removing materials <input type="radio"/> Material can be easily removed from internal cavities, channels, or holes <input type="radio"/> There are no internal cavities, channels, or holes	Mark One Unseasoned features will drop <input type="radio"/> There are long, unsupported features <input type="radio"/> There are short, unsupported features <input type="radio"/> Overhang features have a stopped support <input type="radio"/> Overhanging features have a minimum of 45deg support <input type="radio"/> Part is oriented so there are no overhanging features	x5 = x4 = x3 = x2 = x1 =	
Mark One Thin features will almost always break <input type="radio"/> Some walls are less than 1/16" (1.5mm) thick <input type="radio"/> Walls are between 1/16" (1.5mm) and 1/8" (3mm) thick <input type="radio"/> Walls are more than 1/8" (3mm) thick	Mark One Interior corners must transition gradually <input type="radio"/> Interior corners have no chamfer, fillet, or rib <input type="radio"/> Interior corners have chamfers, fillets, and/or ribs <input type="radio"/> Interior corners have generous chamfers, fillets, and/or ribs	Mark One Hiding parts must not be the same size <input type="radio"/> Hole or length dimensions are nominal <input type="radio"/> Hole or length tolerances are adjusted for shrinkage or fit <input type="radio"/> Hole and length tolerances are considered or are not important	Mark One Large, flat surfaces are important to be exact <input type="radio"/> The part has large, flat surfaces or has a form that is important to be exact <input type="radio"/> The part has medium-sized, flat surfaces, or forms that are important to be exact <input type="radio"/> The part has small or no flat surfaces, or forms that need to be exact	x5 = x3 = x1 =	
Starred Ratings * Consider a different manufacturing process † Strongly consider a different manufacturing process				Total Score 33-40 Needs redesign 24-32 Consider redesign 16-23 Moderate likelihood of success 8-15 Higher likelihood of success	Overall Total +

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Fig. 5 AM worksheet provided by Booth's group [27]

Based on those design guidelines or checklist, the manufacturable geometric features are summarized with design suggestions. They are mainly grouped into six categories: minimum feature size, support structure, part orientation, surface, hollow interiors, and overhangs (as shown in Fig. 6). In addition, those criteria are the major consideration for feature reorganization in the computational methods, which will be discussed in Section 4.1. More details on the manufacturing features for the LPBF process are discussed in the following:

Minimum feature size: Research shows that manufacturable minimum feature sizes exist in the LPBF process [101]. The minimum gap between two features or the minimum wall thickness is two critical examples. In Thomas's research, it is concluded that the minimum gap thickness for LPBF is 0.3 mm, and the minimum wall thickness is 0.4mm ±0.02 [23]. This data is based on the machine and material used in this research. It can be a good reference, but not applicable to all cases. The values vary slightly on different materials and machines. Kruth et. Al [102] examined different LPBF machines with a benchmark to check the process limitations. It was shown that each machine has its own limitations in terms of the minimum feature

size. Moreover, since the material used in the LPBF process is not standardized, and each company has its own proprietary information on the powder they provide, it is not comparable in this case.

Support: Support structure is required in most of the LPBF processes for two main functions: holding the fabricated piece and resisting the thermal stress [103]. However, the support structures will significantly reduce the surface finish [23]. Also, it is shown that improper support structures may cause the failure of printing [103]. Moreover, since the support material and structural material are both metals, they are very difficult to remove. Removing the support structure may significantly reduce the surface finish [17, 104-108]. Therefore, support structures are expected to be minimized. The use of support is a prominent problem in the LPBF process.

Part Orientation: There are two aspects to the part orientation. The first is the placement orientation of the entire part. The second is the angles of the features under the placement orientation of the part. It was found that if an overhang tilts at an angle less than a certain degree from build direction, it may be able to be printed without support structures. The threshold of the overhang structure is defined based on different materials and machines. To minimize the support structures, it is necessary to find the optimal placement orientation to minimize the surface that needs support during printing [17, 23, 25, 26, 61, 104, 107-111]. Most of the slicer software offers such functions to find the best placement of the part. The part orientation is investigated to have significant effects on strength and surface finish. Vertically printed parts with the layers oriented perpendicular to load direction were found to have better mechanical properties than the horizontally printed parts with the layers parallel to load direction [112]. Part orientation decides how many support structures needed for fabricating samples, and removing the support structures will reduce the surface roughness [109].

Surface: Surfaces of the part can be categorized into top surfaces, side surfaces, and bottom surfaces. As the characteristics of the LPBF process, the surface of the part is always attached with incompletely melted powders. To achieve a fully dense metal surface, the part will be printed over-size for post-processing. However, for fine features, post-processing may not be applicable. In this case, the surface roughness will be affected [23, 30].

Hollow interiors: Hollow interior is a type of feature LPBF process specializes in fabricating. Usually, the traditional manufacturing process is not able to produce an entire hollow part at once, but the LPBF process offers this possibility. When the functionality is promised, using the thick wall and hollow interiors significantly reduces printing time and the part weight [17, 104, 113].

Overhangs: Relative long overhangs without support are not printable in the LPBF process. The maximum overhang distance without support varies based on different process parameters. As mentioned above, it is recommended for designers to minimize the support structures when the functionality is promised. When it is applicable, concave and convex radii are alternative design features with self-supporting dimensions [105, 114-117].

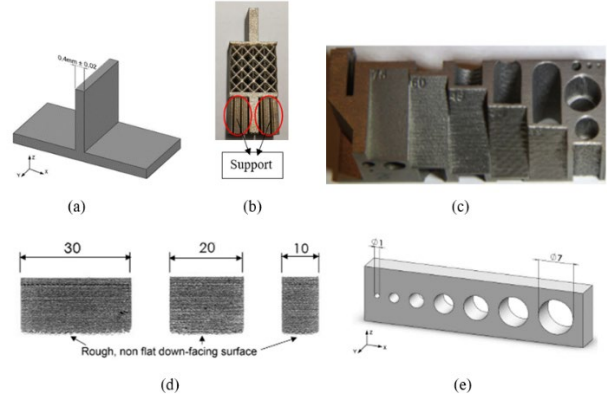


Fig. 6 Examples of geometric features considered in LPBF: (a) minimum thickness [23], (b) support, (c) part orientation [17], (d) surface [23], (e) Holes (overhangs) [23]

3.3. Real-time Process Monitoring

Real-time process monitoring is often used to detect potential failure during printing time. Although the LPBF was invented decades ago, and many commercial machines are available on the market, the process repeatability and stability are still an issue for the industry's breakthrough. Hence, the real-time process monitoring was brought up to improve the process stability. It is also considered as a real-time manufacturability detection. Image-based real-time monitoring is used to detect and predict potential failure and printing quality during the process. The scheme of the process monitoring setup is shown in Fig. 7. Printing failure and unsatisfied printing quality such as surface finish, porosity, tolerance, and tensile stress [63-69] can be found and predicted before completing the printing process in order to save time and save money. Marco[63] has conducted a comprehensive review of the in-situ monitoring methods in metal powder bed fusion in 2017. In his review, he summarized the most categories of defects in the LPBF process such as porosity, residual stresses, cracking and delamination, balling, geometric defects, and dimensional accuracy. A map of the main defects and their approaches causes in the literature was given. Possible sources of defects can be grouped

into four categories: equipment, process, build preparation choices, and material powders. The main set-up parameters and settings for the existing studies are listed in his paper as well. Recently, research on using machine learning to assist real-time process monitoring was proposed to help predict the printing quality and possible printing failure [70-77]. The real-time process monitoring helps detect the printing failure ahead of the completion of the printing and reduce the time and cost. It can effectively help solve the issue caused by the repeatability and stability of the process or machine. However, it lacks the ability to determine the manufacturability in the design stage. It is not applicable if the printing failure happens due to geometric design instead of the printing process or machine.

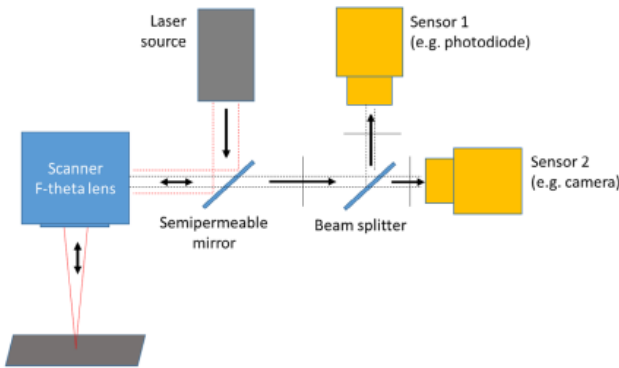


Fig. 7 LPBF process monitoring setup scheme [63]

4. Existing Computational Method in Manufacturability Analysis

Automated manufacturability detection is always the interest of researchers for both industries and academics. In this section, the computational method will be grouped into three major categories: the manufacturing feature recognition, integrated modeling with the consideration of both process and design, and commercial software.

4.1. Manufacturing features recognition

Manufacturing features recognition is the most popular approach to analyze the manufacturability in AM. This approach automates the identification

of erroneous features that are under the capability of the selected printer. The general idea of these approaches is to discretize the 3D model into 2D/2.5D segments to reduce the difficulty of direct identification of 3D features. The detected features will be then evaluated based on the similar criteria listed in the design guidelines (Section 3.2). Moreover, According to the types of input data for feature recognition, prior research can be classified as 3D feature-based approach [78, 79], slicing data-based approach [88, 89], voxel-based approach [80-85], and others [86, 87].

4.1.1. Slicing data-based approach

Chen and Xu [88] proposed an LDNI (layered depth normal images) – based offsetting method for computing thin features in sliced data as shown in Fig. 8. The tunable offset values are consistent with the manufacturing constraints. Nelaturi et al. [83] applied the medial axis theorem (MAT) to identify the thin features in the sliced model. However, MAT has some issues with computing corners. In addition, it is sensitive to small noise and artifacts which results in many unknown branches in the skeleton which requires more work to remove it. Because of those issues, it takes extra computation, and thickness maps for intricate shapes are hard to compute. A more recent advance is realized by the same group [85] by extracting “meso-skeleton” that is the maximal area within each slice where a print head can be positioned during the printing process. It is topologically equivalent to the corresponding slice of the input shape. Their approach allows thickening of the topologically important area that is smaller than the single deposition path. Build orientation is simultaneously optimized to minimize the modification of the original model. The correction of each slice is realized by using pixels (see Fig. 9).

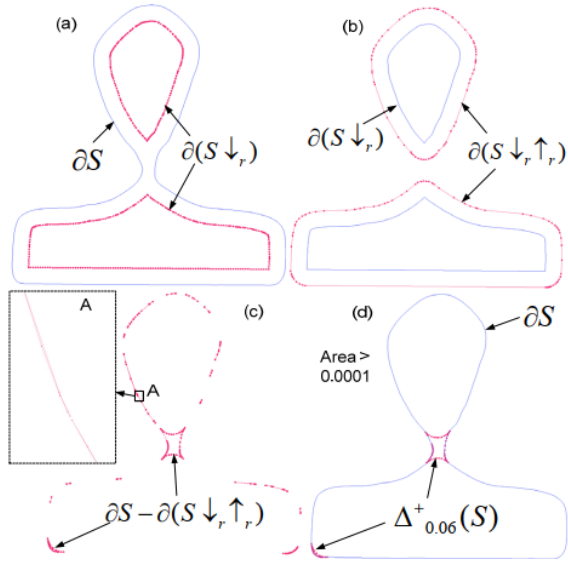


Fig. 8 illustration of computing infeasible features by using LDNI-based offsetting algorithm [88]

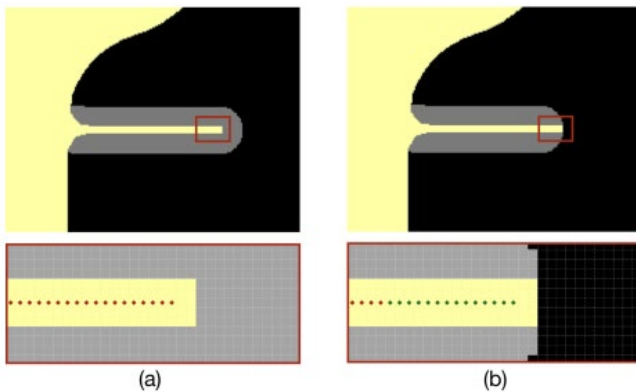


Fig. 9 (a) For the same slice (yellow), when the skeleton is obtained using the thinning process, the protrusion is elongated in the corrected model (gray). (b) Our spur pixel removal allows us to achieve the intended length by deleting the end-point pixels (marked green). [85]

4.1.2. Mesh-based approach

Cabiddu and Attene [89] developed a mathematic model called epsilon-shapes that are able to detect and thicken the thin features in both 2D and 3D geometric models. In 2D geometry, the thickness is computed at the local minimum of each vertex by

triangulation. In the 3D model, the polygonal model has firstly meshed with tetrahedrization, and then the local minimum thickness of each vertex is computed to find global thin features. In general, the mesh-based approach can be seen as the generalization of the voxel-based approach. A scheme of thickness computing for a 2D polygon is shown in Fig. 10. One typical disadvantage of the latter is distortion in the voxelization step. In addition, to meet the high resolution of industrial printers, a 103 centimeters cube would require more than billions of voxels.

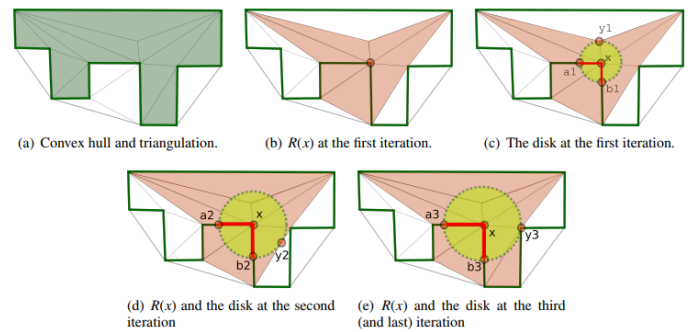


Fig. 10 Computing E for a single vertex. (a) Input polygon with both the convex hull and the triangulation. (b) $R(x)$ at the first iteration. (c) The disk at the first iteration (d) The disk at the second iteration (e) Last iteration in this case [89]

4.1.3. Voxel-based approach

Tedia [81] proposed the approach to the automated manufacturability analysis tool using voxel-based geometric modeling. The input design which is CAD file was first converted into voxel representation. After that, thin features and undersized negative features are identified. Support material generation, void detection, and build time estimation are also considered. The flowchart of his manufacturability analysis was listed in Fig. 11. Several case studies have been conducted to validate his work. Results from the support material generation and build time estimation were compared to the commercial software to validate his approach.

Though his case study was fabricated through the material extrusion process, which is another type of AM process, the idea is similar in the LPBF process.

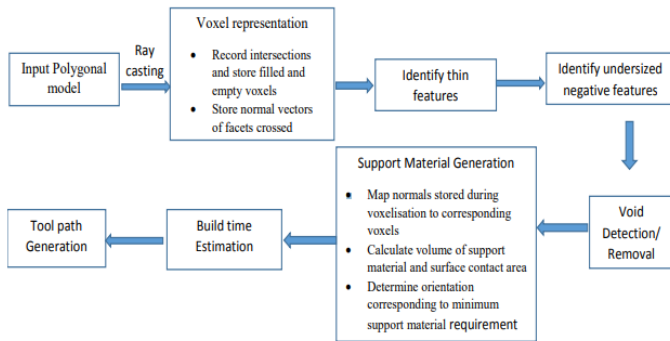


Fig. 11 Flowchart of the manufacturability analysis tool [81]

A more advanced approach proposed by Kerbrat et al. [80] introduced an octree-based voxelization approach to decompose a CAD model for hybrid additive and subtractive manufacturing. Manufacturability index covers geometric

information (maximum and minimum dimension, geometric accessibility, radii, void volume, etc.), material information (material availability and material properties), and technical specifications (tolerance and surface quality). An example of 2D octree-based voxelization is shown in Fig. 12. The octants are categorized into three categories: black octants, white octants, and grey octants. To construct an octree, the object is first enclosed by the root octant that can completely contain the object in any direction. It is then subdivided into eight sub-octants to get the first level of the octree representation. Black octants are those that are completely inside the object. Grey octants depict those that are partially inside and outside the object. White octants stand for those that are completely outside the object. The subdivision process will be performed on grey octants until the desired resolution is achieved. Based on the octree decomposition algorithm, a map of manufacturing complexity is obtained.

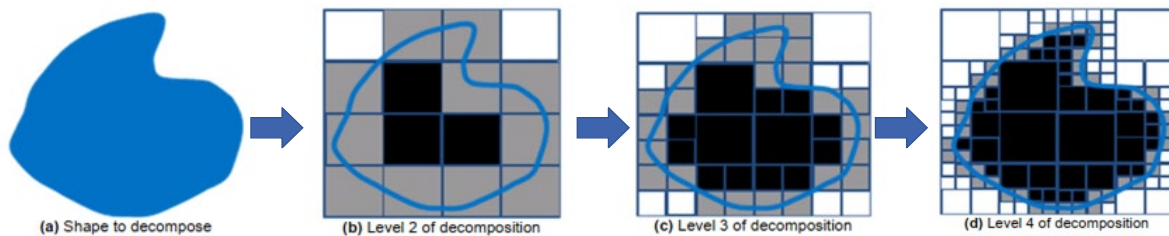


Fig. 12 Octree-based voxelization [80]

4.1.4. 3D feature-based approach

Shi et al. [79] first listed infeasible features including unsupported features, minimal feature, maximum vertical aspect ratio, minimum clearance, and minimum support-free angle. Heat Kernel Signature (HKS) is adopted to cluster surfaces based on vertices with triangular meshes as the original input. The basic idea of HKS is to compute the heat losses through time. The heat diffusion rate is

deemed an indicator of the topological and geometric entities. In order to obtain the rate, the heat diffusion equation is applied. The rate is represented by the quantity of heat received by a point after a unit. With the heat persistence value and a percentage similarity, the vertices can be clustered into different sets in order to predict a mass distribution pattern and to prepare the potential shape recognition as shown in Fig. 13.

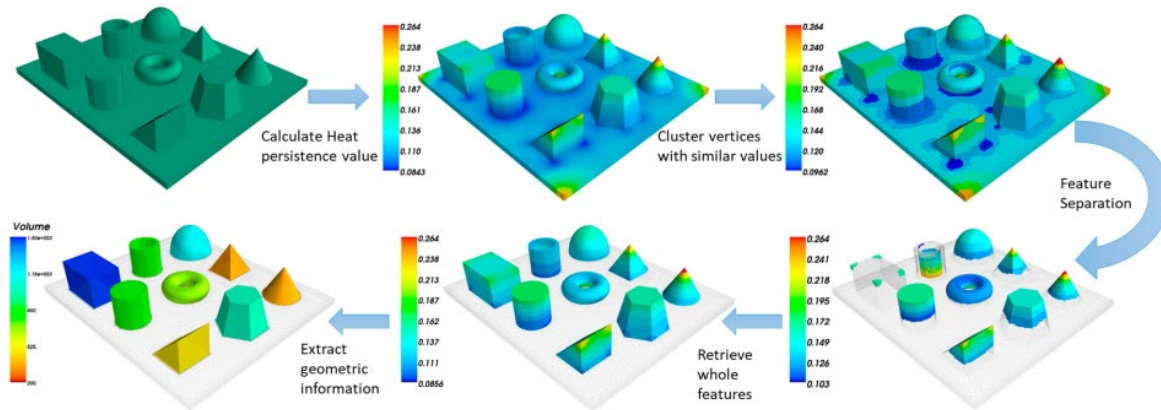


Fig. 13 the flow of feature recognition using HKS [79].

4.1.5. Rule-based approach

The printability checker provided by Lu [86] was established to accomplish a similar job. The novelty of his work is using the machine learning method to help the checker to determine the manufacturability based on a repository of the .stl file labeled printable or not instead of relying on the strict assessment. He validated his approach with 0.9 accuracies on 20 training examples and then applied the same model on 619 .stl files. The prediction accuracy was higher than 0.92. The framework of his approach was shown in Fig. 14. However, in his validation, only bounding box features were considered as the input features to the machine learning method. For the rule editor, only comparing the bounding box to the printer volume is not enough to determine the printability. The author provided an abstract level analysis on the manufacturability, and more works need to be done in the future. Kim et al. [87] developed an ontology-based knowledge repository to support rule-based retrieval of AM constraints. Based on which, manufacturability can be tested with users' inputs of the semantic description of feature parameters. In this work, constraints, such as thin feature, clearance, overhang feature, and support structure are investigated. In general, the level of automation of retrieval-based approach is very limited.

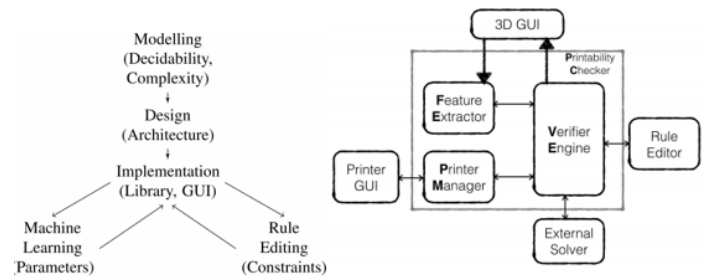


Fig. 14 Printability checker architecture [86]

4.2. Integrated Modeling

Manufacturing feature recognition mainly considers the effects of the design aspects, but not the process aspects. The performance of the printed part may vary due to the variation of the machine selections, material selections, and the setting of the process parameters. To fill this gap, researchers such as Hossein et al. [91] integrated the performance of the parts and the AM process into a model to predict the performances of the AM parts and to improve the design and processes. They proposed the dimensional analysis conceptual modeling (DACM) framework to generate the interrelationship among performance model and process model by producing a set of governing equations.

A similar idea generated by Xu's group [90] presented a knowledge management system using Bayesian networks. The method was referred as the Guide-to-Principle-to-Rule approach. The model

was set based on AM fundamentals. The structure of the system is presented in Fig. 15. The knowledge management system was organized into three domains: process, material related, design-related, and part related. Each domain was quantified. The manufacturability was modeled numerically from the top level to the detail level. The system can learn conditional probabilities in the model from different sources of information, and inferences can be conducted in both forward and backward directions. Users are expected to use this management system to determine the best AM process that can be used prior to the real fabrication. Also, the estimated dimensional accuracy, mechanical properties, and surface finish are given in a range. Note that different from other computational approaches which mainly focuses on the feature recognition, Xu's approach is trying to model the relationships among the process, design, and product qualities of the AM process, but not intended to make a precise prediction on the manufacturability of a given design. It offered a well-modeled knowledge management system on the AM process, and it was intuitive for users to understand the manufacturing process. However, when applied to the specific design, uncertainties from different printing strategies and printers are not considered. It can help the designer to understand the AM process better, but users still need some knowledge to make a decision on whether their designs are manufacturable or not.

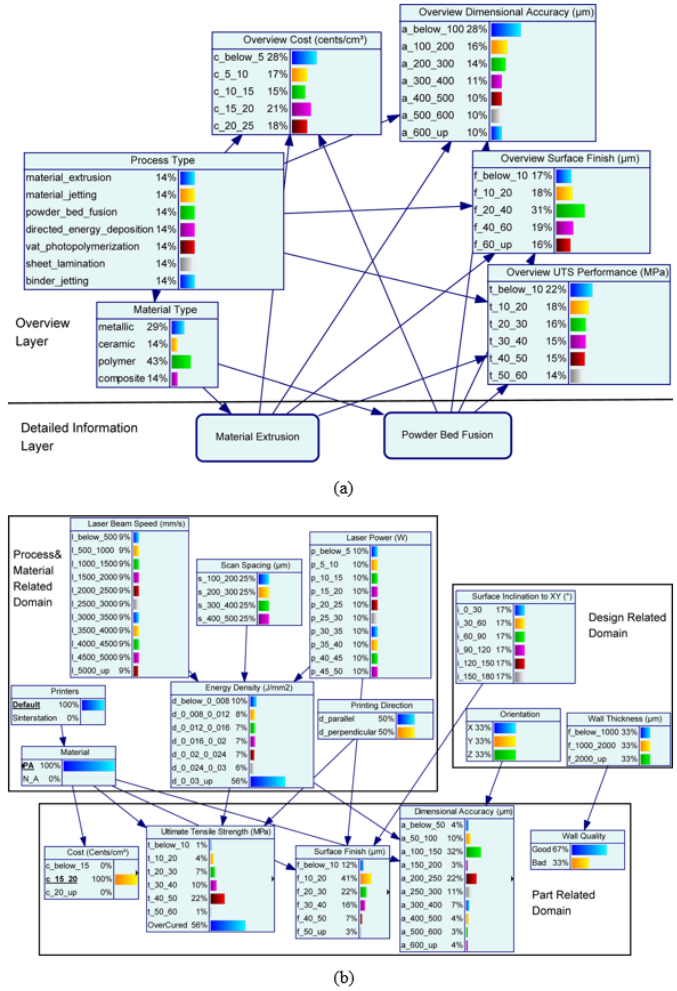


Fig. 15 Structure of the knowledge management system: (a) overall structure, (b) submodel for LPBF [90]

4.3. Tested commercial software

While preprocess software exists such as Magics, Netfab, and online 3D printing service providers such as Sculpteo, Shapeways, 3D hub, and 3DXpert, they are focused on examining the validity of STL files and repair of meshes and offering the functionality of slicing, toolpath planning, infill pattern, boolean operations, and support structure generation. More recently, some software provides options for optimizing the build orientation and the support for the part. Some of them offer the function of recognizing and examining the small feature which is under the resolution threshold such as thin

walls; however, they are specific for a type of printers, and other types of difficult-to-manufacture features are not included such as void and minimum clearance.

In conclusion, the current automated approaches have been presented recently to identify problematic regions, and they are demonstrated to provide valuable design feedback to users by determining the compatibility of a 3D model with the printing hardware. From the review, it shows that the voxel-based approach enables the detection of multiple infeasible features, and it is promising in relatively low computational cost. However, the manufacturability is not only affected by the build orientation, support material, and minimum feature size. The major approach for the computational method offers a simple geometry check for the design. It provides the recommended orientation and support structure for the current design based on the algorithm. However, in addition to the thin features and overhangs, it lacks the ability to provide the suggestion for the designer whether their design features are manufacturable or not.

5. Fundamentals of the Manufacturability Analysis of LPBF

This section will provide an overview of the fundamentals of evaluating the manufacturability of the LPBF process. It will introduce a new definition of the manufacturability of LPBF following by an overview of the manufacturability level. The major effects on evaluating the manufacturability are summarized as well to guide future research.

5.1. New Definition of the Manufacturability of LPBF

As discussed in Section 3.1, the definition of the manufacturability of the LPBF process is vague, and a clear new definition is needed. Depends on different applications, the required quality of the printed parts typically varies. Manufacturability may need to consider the effects from each stage of the general LPBF workflow including design,

fabrication, and post-processing. For the post-processing, whether the fabricated parts can bear the force from the post-processing can be an issue. The printed parts can be fractured during the post-processing. In the fabrication process, stability could be a critical issue during the printing process. Even after successfully building the part, whether it satisfies the product's requirement can be another issue. Therefore, it is hard to provide a general definition of the manufacturability of LPBF. However, it is possible to define the manufacturability at the design stage. In most cases, manufacturability refers to the design characteristics which indicate how difficult or easy the design is from a manufacturing perspective [118]. When considering the design process, Fig. 16 shows the role of manufacturability analysis in the design process. Engineering analysis is to determine whether current design and materials can satisfy performance requirements. Manufacturability analysis is to ensure the part can be well fabricated based on defined design, materials, and manufacturing processes. The focus of manufacturability analysis is to determine whether the specific design with the defined material can be printed in the desired shape using a certain machine with the fixed process parameters. In the literature, common physical features reported in LPBF can be dimensions, porosity, and density [119]. Cracks and pores are one of the terms frequently used to determine the behavior of the products [119, 120]. Generally, materials with decreasing cracks and pores have increased tensile strength, young's modulus, strain-to-failure, and fatigue strength [121]. Generally speaking, if the product is a dense metal part, it is defined as a qualified part for functionality in the manufacturability analysis. Hence, the manufacturability of the LPBF at the design stage can be defined to consist two aspects:

- Geometric inconsistency between the design model and the built model which includes shape

and dimensional error. Whether the geometric features of the design can be built or not.

- Functional inconsistency between the design model and the built model which includes the manufacturing defects and the heterogeneity in properties. Whether the quantity of density and porosity and cracks in the fabricated part meet the standard.

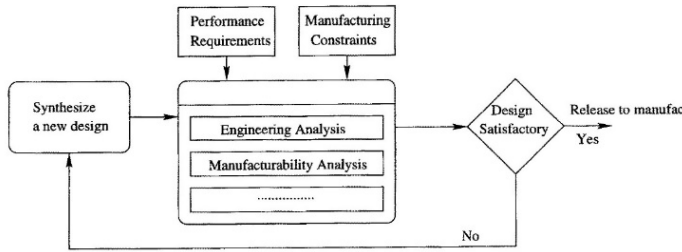


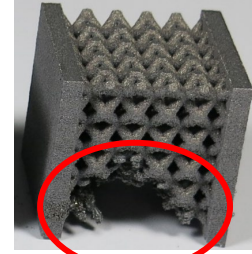
Fig. 16 Manufacturability analysis in the design process [122]

This definition can be used to guide future research on the manufacturability of the LPBF process. The fabricated part which satisfies the requirements of the two defined aspects is considered to be manufacturable. Therefore, for future researches, the proposed definition can be used as the standard to determine the manufacturability level of the LPBF process.

5.2. Manufacturability Levels based on the New Definition

Based on the new definition, the manufacturability level of a given design can be determined by the following:

Manufacturability Level 1: The printed part should be free of visual defects such as geometric incompleteness and warping (Fig. 17).



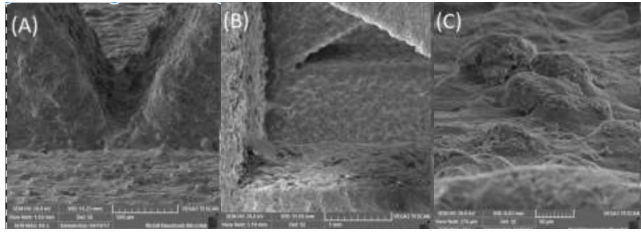
(a)



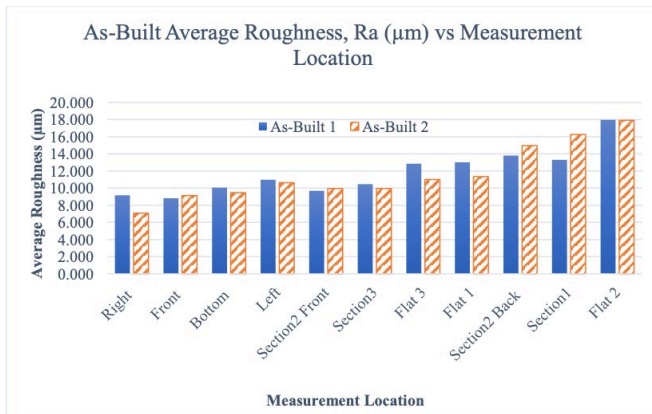
(b)

Fig. 17 Example of (a) geometric incompleteness and (b) warping

Manufacturability Level 2: At level 2, the printed part should first meet all the requirements from level 1. Then, it will be compared to the original design to calculate the dimensional error. The printed part will be evaluated based on the customer requirements to determine whether it meets Level 2 or not. The requirement can be specified on certain dimensions such as hole tolerance, roughness, straightness, side dimension, etc. Fig. 18 provides examples of Scanning Electron Microscopy (SEM) results and a table which lists the measured roughness at selected points [123]. The requirement also can be an overall dimensional error. It can be calculated by comparing the dimensional profile of the printed part to the design file.



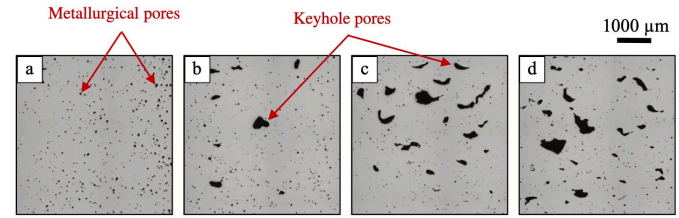
(a)



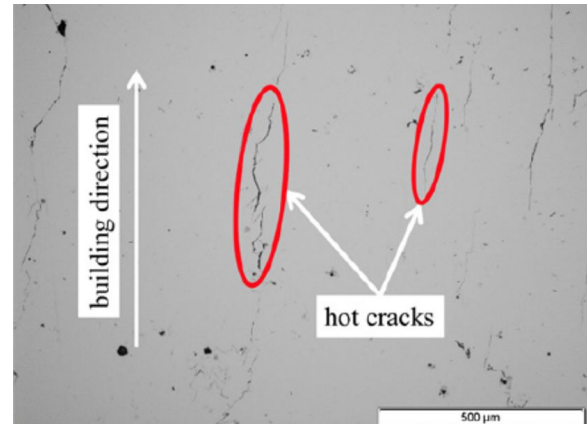
(b)

Fig. 18 Example of (a) SEM images and (b) Roughness analysis for the printed parts [123]

Manufacturability Level 3: At the third level, the printed part should first meet all the requirements from Level 1 and 2. Then, the quantity of the density and porosity and cracks should be obtained at this level. Chee et al. [119] have explained the details of the metrology measurement methods on measuring those characteristics. The printed part is identified to achieve Level 3 once it meets the requirements on the quantity of the density and porosity and cracks (Fig. 19).



(a)



(b)

Fig. 19 Example of (a) pores and (b) cracks [124]

Finally, the printed part can be defined as manufacturable through the LPBF process once it meets all the requirements of Level 3. Moreover, for future research, the manufacturability analysis can be separated into stages based on the manufacturability levels to achieve the goal.

5.3. Major Effects on Evaluating the Manufacturability

To investigate the manufacturability of the LPBF process, there are three key aspects that need to be considered: design, process, and material (Fig. 20). The manufacturability is the intersections of these three aspects. Thus, it is necessary to understand all three aspects. Process and material are often correlated to each other and combined as process parameters.

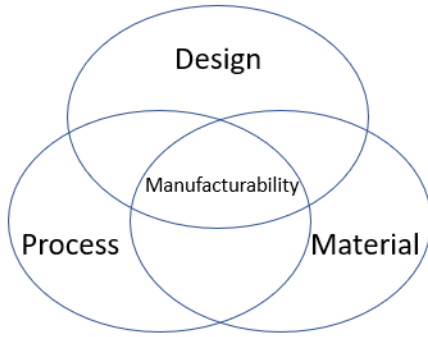


Fig. 20 Manufacturability of LPBF

To consider the manufacturability of a manufacturing process, consideration must be given on what geometric features can be fabricated. In the conventional manufacturing process, the major design geometric features were defined as holes, slots, pockets, etc. which are typically associated with the type of the corresponding tooling needed to make these features [49]. However, the design geometric features that the LPBF process can manufacture are drastically different from those defined for CM processes. More importantly, it was found that if a design geometric feature is manufacturable by one LPBF machine with one given process parameter setting, it may not be manufacturable when the machine or process parameters are changed [102]. In Kruth's research [102], the major design geometric features considered in LPBF are thin walls, overhangs in holes, self-supporting holes, one angled surface, and large radiuses. A few benchmark testing parts were designed to identify the limitations and accuracy of the LPBF process. After that, Thomas [23] did numerous experiments to establish the design guidelines for the LPBF process. The main geometric features considered in this research are object-orientation, surface roughness, minimum slot, and wall thickness, parallel edge, angular overhangs, fillet radii, holes, and channels, tapping, and reaming a self-supporting hole, shrinkage, and stock on the material. Later, Adam [24] investigated the design rules for AM including LPBF. The limitations of thickness, orientation, direction, and

position of wall feature as well as the length, inner radius, orientation, and outer radius of the cylinders were studied. Similar studies were also carried out in industries to identify geometric feature limitations in LPBF processes. Materialise [125] provides design guides based on their machines for 20 different materials. Taking steel as an example, wall thickness, overhangs, connections, edges and transitions, holes, wireframe structures, hollows, nested objects, hinged and interlinking parts, connection marks, text, and surface details, shrinkage compensation, and dimensional accuracy are the main considerations [126]. Similar guidelines are given by Stratasys [127] as well in the form of design guides for different AM process. In the most recent literature, major geometric features considered in the LPBF process can be summarized as minimum feature size, overhangs, shrinkage, and object building orientations which have been discussed in Section 3.2.

The process parameter is another consideration in the manufacturability analysis. Research shows that there are more than 130 process parameters influencing the LPBF process, but only a few of them are critical [39, 128]. These process parameters were grouped into four groups: laser-related, scan-related, powder-related, and temperature related. In the laser-related group, it consists of laser power, wavelength, spot size, pulse duration, pulse frequency. In the scan-related group, it comes with scanning speed, scanning spacing, and scanning patterns. In the powder-related group, it has particle size and distribution, particle shape, powder bed density, layer thickness, and material properties. In the temperature-related group, it contains the powder bed temperature, the powder feeder temperature, and the temperature uniformity. The full list of process parameters can be found in Fig. 21. Most of these parameters are strongly interdependent and interacting. For example, steel may need laser power at 150W to have better quality, but for other materials such as aluminum, preferred laser power is different [129]. Even for the same

material, different particle sizes, shapes, and density will also need different laser power to achieve the best quality. Other factors such as gas flow also have a significant influence on the quality of the final products [4]. Researchers have conducted many studies to investigate the interrelationship between process parameters and product qualities.

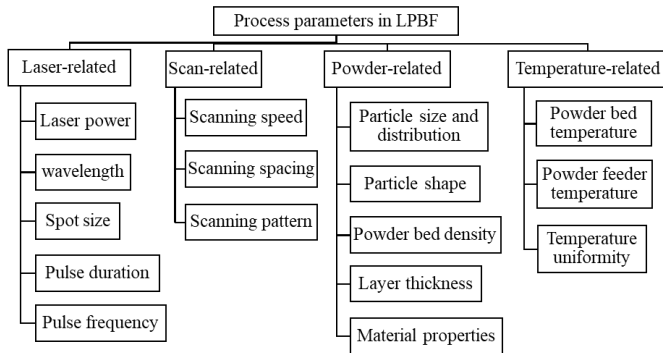


Fig. 21 The principle process parameters in LPBF [39]

6. Discussion and Research Issues

6.1. Comparison of manufacturability analysis between CM and LPBF

For the manufacturability analysis in the CM process, the approaches are summarized as two categories: feature-based approach and feature-less approach. The geometric algorithms are similar in both approaches which are either slice-based, volume-based or hint-based. The difference is that, for the feature-based approach, the focus is on identifying the machining features such as holes, extrusion, plane, etc. For the feature-less based approach, the major investigation is to evaluate the four machining characteristics which are visibility, reachability, accessibility, and setup complexity directly on the geometries, so there are no feature extractions. For the manufacturability analysis of the LPBF process, it mainly focuses on the feature-based approach. There are very few studies on the feature-less approach. The geometric algorithms for analyzing the shape are similar to the CM process; however, the target features in the LPBF process are different from the features in the CM process. The

LPBF process focuses on features such as minimum thickness, overhangs, etc. In addition, there are no defined manufacturing characteristics like the CM process. The manufacturability analysis is based on the constraints on those target features. For instance, the minimum gap thickness for LPBF is 0.3 mm, and the minimum wall thickness is $0.4\text{mm} \pm 0.02$ [23]. Moreover, the CM process removes the volume from the raw materials; hence the quality of the same machining process should be nearly the same. However, for the LPBF process, the printing quality with different selections of the AM machines might be different. It states that, when considering the manufacturability of the LPBF process, not only the geometries of the design, but also the process settings and the material selections should be considered as well. Although the existing approaches in analyzing the manufacturability of CM may not be able to apply in the LPBF directly, it still has referential importance in researching the manufacturability of the LPBF process. As a mature manufacturing process, those existing approaches can be a good start point and guidelines to further investigate the manufacturability of the LPBF process.

6.2. Gaps in the existing approach in manufacturability analysis

LPBF is a type of AM process that can produce highly complex structures that have high potentials

for industries ranging from aerospace, medical, and automobile industry. As a relatively new manufacturing process, its capability, typically referred as manufacturability, is still not well understood. Reported approaches on modeling manufacturability of LPBF were introduced in previous sections which included design guidelines/checklists, real-time process monitoring, and computational method in manufacturability analysis. Although a number of research studies have been conducted to investigate the manufacturability of the LPBF, there are still some gaps in the literature.

As defined in Section 5.3, to fully investigate the manufacturability of the LPBF process, both design and process aspects need to be considered. However, the relationship among the process, design, and printing qualities of the parts are not well modeled in the literature. Although there are many studies to investigate the relationship between the process and

printing qualities or between design and printing qualities, manufacturability is a more complex issue that requires the consideration of processes, materials, and designs simultaneously. In existing approaches, which are shown in Table 2, none of them comprehensively consider both design and process aspects.

Table 2 Comparisons among each manufacturability analysis approach in the literature

Approaches		Design guidelines/checklists	Rea-time process monitoring	Computational Method	
				Feature recognition	Integrated modeling
Design consideration	minimum feature size	Yes	No	Limited	Limited
	overhangs	Yes	No	Yes	Yes
	shrinkage	Yes	No	No	No
	building orientations	Yes	No	Yes	Yes
Process consideration	material selection	No	Yes	No	Yes
	machine selection	No	Yes	No	Limited
	process parameter settings	No	Yes	No	Limited
Automatic		No	Yes	Yes	Limited

Design guidelines are the most reliable method for designers to get design standards for the LPBF process. However, this approach requires designers to have extensive knowledge and experience in the LPBF process. The guidelines are typically represented in an abstract form and require extensive human interpretation. In addition, it does not consider the effects of the process aspects such as material selection and process parameters. It is an acceptable method for industries and professionals, but not recommended for beginners. The design worksheet is considered as a simplified guideline. It is easy to follow and suitable for beginners who are new to LPBF machines, but it only works for simple geometries. It is good to be used as the first filtration

on a given design, but deeper evaluations are needed later. Real-time process monitoring can be another approach to help increase the printing successful rate. However, it does not offer any help at the design stage. The most existing computational methods in manufacturability analysis have been presented recently to identify some problematic regions, and they are demonstrated to provide valuable design feedback to users by determining the compatibility of a 3D model with the printing hardware. However, there is no unifying approach enabling examination of manufacturing constraints that are specific to the LPBF, and most of them fairly consider the process effects on the final printing quality. The integrated modeling is different from the most computational approach. It is the most intelligent and user-friendly

method. However, it offers limited information on both the process and the design aspects. Moreover, each LPBF machine from different machine makers has slightly different settings. This method needs to be modified by experts of each type of machine to ensure successful printing. Therefore, a well-developed automatic manufacturability analysis tool that considers both design and process aspects is highly in demand.

7. Conclusions and Perspectives

In this paper, reported literature related to the understanding and investigation of LPBF manufacturability is reviewed and discussed. There are very few studies that have been published to review the manufacturability of LPBF. Research showed that there is no proper or standardized definition of what manufacturability of the LPBF process is, and there is no suitable model to comprehensively represent manufacturability associating design features, process parameters, and end part qualities. This survey paper provides an overall idea of how past researchers investigated on the manufacturability of the LPBF and what characteristics they focused on. The approach to defining the manufacturability of the LPBF was proposed as well. More comprehensive analysis either from design guidelines or automated analysis tools on the manufacturability of LPBF is expected in the next few years. At last, based on the review, several future works concerning the manufacturability of the LPBF process have been pointed out:

- Most existing manufacturability analysis of the LPBF process proposed the general idea on all the AM technologies. There are very few studies that carefully considered the uniqueness of the LPBF process. More comprehensive studies on the manufacturability of the LPBF process should be conducted in the future.
- The existing studies on the automatic manufacturability analysis of the LPBF process mainly focus on feature recognition to detect the machining features. However, there are very limited numbers on the feature-less approach. Feature-based approaches are restricted to the complex geometries. The integrated modeling offers one potential solution to the feature-less approach, but it is still limited and theoretical. A new feature-less approach should be proposed in the future with consideration of both design and process aspects.
- There is no existing approach that is able to automatically identify all types of infeasible features for the LPBF process given a large number of different machine and process settings. Users highly depend on heuristic design guidelines developed by benchmark studies. Existing preprocessing software (e.g., Magics, Netfabb, 3DXpert) mainly offers functions of quality check and reparation of STL meshes, slicing, support structure generation, and limited functionality of overhang and thin wall detection. The need is increased for the tool which helps to visualize the troublesome areas and give feedbacks for modification.
- Most of the existing literature focuses on determining whether a given design is manufacturable or not for a selected AM technology. For the purpose of the manufacturability analysis, a completed design for the manufacturing planning system for the AM process is needed. The planning system should be able to provide feedback or generating alternative AM processes or AM machine selections for designers to successfully build their design.
- Currently, the manufacturability analysis is primarily considered at the design stage, but the printing process and post-printing process can also be considered as part manufacturability. Especially for the post-processing, there are very few studies working on this area.
- With the rapid growth of the LPBF process, the process and the corresponding commercialized machines have been refined and updated

speedily. The part may not be fabricable in a certain machine this year, but it may be successfully printed in the next generation of the machine. The factor should be taken in mind as well when analyzing the manufacturability of the LPBF.

8. Acknowledgment

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