DESIGN RULES FOR ADDITIVE MANUFACTURING: A CATEGORIZATION

Mahesh Mani[a]
Allegheny Science and Technology
DOE Contractor
Washington, DC 20024
mmani@alleghenst.com

Paul Witherell
National Institute of Standards and Technology
Engineering Laboratory
Gaithersburg, Maryland 20899
paul.witherell@nist.gov

Jacob Jee
Hong Ik University
Department of Mechanical & System Design
jacobjee@hongik.ac.kr

ABSTRACT

Additive manufacturing (AM) is gaining popularity in industrial applications including new product development, functional parts, and tooling. However, due to the differences in AM technologies, processes, and process implementations, functional and geometrical characteristics of manufactured parts can vary dramatically. Planning, especially selecting the appropriate AM process and material requirements can be rather involved. Manufacturability using AM processes has been well studied; however, gaps exist in the design process when catering to the needs of manufacturability. Designers today are challenged with a lack of understanding of AM capabilities, process-related constraints, and their effects on the final product. Challenges are compounded by the ambiguity of where design for AM ends and process planning begins. These ambiguities can be addressed through design principles and corresponding design rules for additively manufacturing parts. The purpose of this paper is to categorically present relevant and reported efforts in design and process planning with design rules in AM. The overarching goal of the review is to offer insights to extract and categorize fundamental principles for derivative rules for different AM processes. Identifying such fundamental requirements could potentially lead to breakthroughs in design and process planning.

Keywords: additive manufacturing, design rules, design guidelines, category principles, design for additive manufacturing

1. INTRODUCTION

Additive manufacturing (AM) is the process of joining materials to make objects from digital representations, layer upon layer, as opposed to subtractive manufacturing methodologies [1]. The ability of AM to build parts directly from a 3D model makes it a promising alternative when compared to traditional manufacturing (e.g. machining, injection molding, and die-casting) for rapidly producing highly customized parts. Today, additively manufactured parts are particularly gaining popularity in industrial applications. Various opportunities of AM processes and techniques, their applications in diverse industry sectors [2–14], and the influence of AM in production systems to enable a new paradigm of cost-effective manufacturing [3,15–20] have been well documented.

Though AM generally refers to the building of parts layer-by-layer, the sets of processes are based on different technologies and cater to different materials. The diversity of materials used in AM currently covers metallic, plastic, ceramic, or composite materials in different forms, such as powders, wires, filaments, or liquid. AM processes that have been previously categorized by different researchers under different names such as rapid prototyping, additive fabrication, freeform fabrication, 3D printing, and rapid manufacturing [2,4,21,22] have been standardized by the ASTM International Committee F42 on AM Technologies and ISO TC 261 [1] into the seven classes based on the underlying technologies.

Due to the differences in AM technologies, processes and materials used, functional and geometrical properties of manufactured parts can vary dramatically. Planning decisions to select the appropriate AM process and material based on specific application requirements can be rather involved [22–24]. Designers today are challenged with a lack of understanding of AM capabilities, process-related constraints and their effects on the final product [25–27]. Designers need new methods to assist in selecting optimum AM processes settings, associated materials, or appropriate designs for a given AM process, e.g., based on features, size, surface finish, or tolerances [28–31]. Correlations related to AM process parameters, process signatures, and product quality provide a means to understand the dimensional tolerances, surface roughness, and defects that limit the broader acceptance of AM for high-value or mission-critical applications [32].

Previous AM roadmap workshops have broadly identified the need for AM design rules and decision support tools [33–35]. One such workshop [35] specifically explored the challenges in developing formalized design rules and expert advisory tools. We argue this concept of formalized

[a]While at National Institute of Standards and Technology

design rules must be further explored to address the challenges set forth in these roadmaps. In particular, we advocate the development of fundamental principles to help establish variations of geometry-material-process-structure relationships and facilitate future development of expert systems and design allowable databases.

In [36,37], Jee et al. proposed methods for developing common vocabularies for design rules. The work presented in this paper builds on previous work through the categorization of these fundamental principles. We first present, analyze, and summarize previous efforts on design rules in AM. We then build on these findings to categorize fundamental principles used in different AM processes.

2. LITERATURE REVIEW

Several research efforts have emphasized a need for design rules that relate AM processes, capabilities, and materials [38–40]. A few reports have articulated the need for a design methodology, promoting design techniques such as feature-based functional design, design for tolerances, design based on capabilities, and attention to wall thickness, etc. [23,26,28,34,41,42]. This review focuses on design and process planning in AM, and we explicitly differentiate between guidelines and rules. While much work has been tailored to the development and creation of guidelines (including books, standards, etc.), less attention has been allocated to the derivation of a fundamental philosophy on how this knowledge can explicitly derived and communicated. Our investigation focuses on the identification of these fundamentals that will support the identification, characterization, and specialization of design rules in AM.

When considering the future of AM, critical requirements have been identified as high process stability, a reference database of AM materials and properties, and the provision of design rules [34]. Today, design rules are gaining international attention. For AM, part design driven by functional needs is the key to success, and a strategy for building the basic ground rules for design. A number of factors such as the part size, part accuracy, surface finish, mechanical properties, and functional requirements are all considered during process selection for a given design [4,27]. The design freedoms enabled by AM capabilities are reflected in the following four categories: shape complexity, hierarchical complexity, material complexity, and functional complexity [4]. Challenges arise when designers who are unfamiliar with AM desire to exploit design freedoms through informed design trade-offs. By focusing on design rules that are flexible enough to accommodate these attributes, one can make informed decisions on suitable geometries, processes, process parameters, and materials.

Several researchers have addressed the development of design rules based on traditional manufacturability [26,34,43–47], and assessed the impact on the design process [2,28,48], and thus further incorporated geometry into any guidance. Khaln et al., discussed a redesign selection criteria based on *integrated design*, *individualization*, *lightweight design and efficient design* to fully exploit the geometric freedom of AM [49]. Campbell et al., [48] in particular identify that there is no systematic design tool available to guide designers through value-added suggestions that can be evaluated once embodied into the product design.

As a design facilitator, design rules must consider design potentials, design restrictions, and process capabilities. To effectively support AM design freedoms, design rules should be product independent and universally applicable amongst AM processes [50]. According to the Direct Manufacturing Design Rules (DMDR) project [51], the key aspects of design rules include design for function (functional integration, design potentials, etc.), design for tolerance (e.g. physical restrictions), and capabilities (speed, accuracy, repeatability, material, etc.). In their work, design rules were developed based on standard elements (e.g. cylinders, corners, and joints), element transitions (e.g. firmly or loosely bonded), and aggregated structures (e.g. overhangs). Each standard element has different attributes (e.g. thickness, length, width, orientation, position, and direction). The idea follows that for designing technical parts, standard elements can combine and attribute values varied to fulfil the part's function. The intention was to be function-independent and easily transferable on individual product designs (See Figure 1).

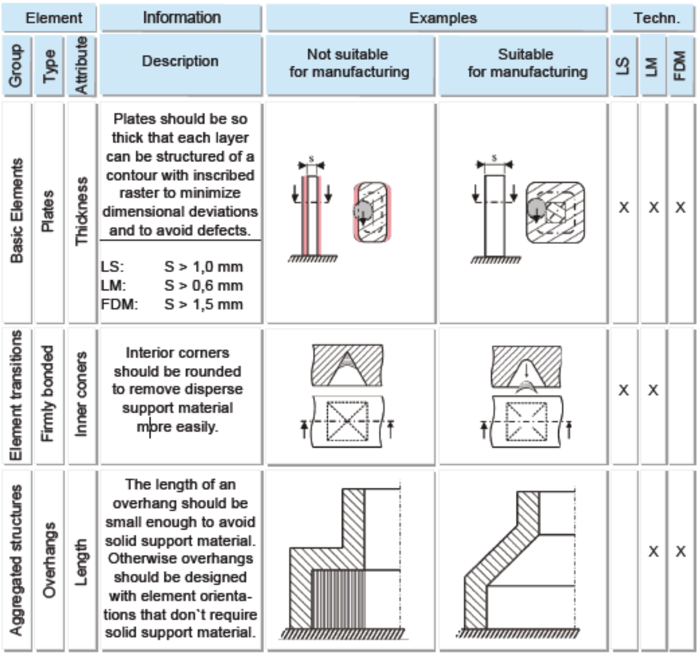

Figure1 Standard elements and design rules (Reproduced from [51])

Several reports have specifically identified the practice of Design for Additive Manufacturing (DFAM) [28,52–55]. Tang et al. [56] reviewed design theory and methodology (DTM) in the context of AM, arriving at the conclusion that DTM is not qualified to embrace these new opportunities. Consequently, in their work, available AM design methods were reviewed and classified into three main groups: design guidelines, modified DTM for AM, and design for additive manufacturing (DFAM). They later propose a new design method involving function integration and structure optimization to realize less part count and better performance [57]. In similar works, Vayre et al. [58] proposed a four step methodology for validating a proposed AM part design. The first step analyzes the specifications of the part, then a single or several rough shapes are proposed. These shapes are topologically optimized in relation to the specifications and the manufacturing constraints. Finally, the proposed design is validated. Though these approaches are effective in their own rights, they are not optimal for design and process planning. Essentially, a rule base should provide a comprehensive matrix of all possible permissible combinations of process parameter values to produce defect-free AM parts.

Outside of academia, industry has begun to embrace the practicality, or even necessity, of guiding design and process planning. Specific to metals, a few manufacturing reports have discussed design rules for AM based on experiences and best practices [59–61]. These efforts have been supplemented by similar efforts of individual service providers [62,63]. Such rules are usually based on data format, build envelope, part orientations, part tolerance, wall thickness, pin sizes, holes, stair case effects, etc. Specific correlations specified by these rules are essential in effectively communicating design and process planning considerations so tradeoffs can be understood and decisions can be effectively made.

To take advantage of AM processes, it is necessary to identify and understand their specific manufacturing capabilities as well as their inherent manufacturing constraints. Some general AM design guidelines based on manufacturing experiences and best practices were earlier reported [45] (Becker et al., Yan et al). Best practices where used to derive example rules such as: optimize a design towards highest strength and lowest weight, use undercut and hollow structures if they are useful, or reduce the number of parts in the assembly by intelligent integration of functions.

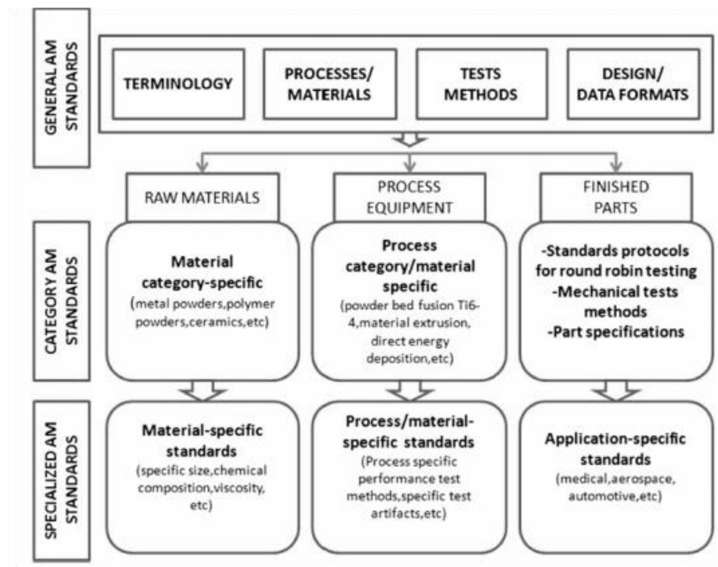

Figure 4 Standards related to AM (Reproduced from [4])

2.1. Standards efforts

The AM industry needs standards to facilitate communication and collaboration in product development, ensure process and material qualification, and promote modular and reusable systems and subsystems [64]. To be useful to designers, design guidance needs to consist of rules with numeric values capturing the limitations of AM technologies, processes, and machines. In general, the AM industry currently lacks fundamental principles for establishing derivative rules based on guidelines and best practices.

Industry practices to derive and represent design rules are often inconsistent with each other, partially due to a lack of uniform methods to represent design criteria and relate it to AM processes and equipment performance. Characterizing systems and collecting the data needed to understand design trade-offs has become a challenge for the AM industry. To address this challenge, among others, standards development organizations are developing standards to assist AM industry. For instance, the ASTM Subcommittee F42.04 on Design, in conjunction with ISO TC261, focus on topics such as Guide for Design for Additive Manufacturing, Specification for AMF Support for Solid Modeling, and Principles of Design Rules in Additive Manufacturing. A recent effort led by ANSI and America Makes, the Additive Manufacturing Standardization Collaborative, prioritized several types of design guidance in future standard development needs.[2]

Of immediate relevance to this paper is a new effort on developing a guide for principles of design rules in AM (ASTM WK51841). This guide seeks to homogenize fundamental design-process-material correlations within AM processes. Focusing on function- independent rules based on elemental design features (geometric and mechanical features) can provide the needed reference when additively manufacturing parts. Such standardized design rules aim to make AM production of parts repeatable.

3. PROPOSED GUIDE-TO-PRINCIPLE-TO-RULE METHODOLOGY

Section 2 emphasized the need for AM rules based on criteria such as part manufacturability, process constraints, best practices, materials, and standards. It is evident that there are inconsistencies in design rule representation because of a lack of uniform methods to represent design criteria and relate it to AM processes and equipment performance. Accordingly, in this section, we revisit and further an earlier proposed approach [36,37] to establish elementary principles as a starting point to promote the consistent development and application of design rules to mitigate ambiguities.

Where previous work focused on establishing basic fundamentals, this work proposes an approach that focuses on the deriving principles from literature in a way that they can be easily incorporated into design rules. The *Guide-to-Principle-to-Rule (GPR)* approach is summarized in Figure 5, where we derive the *Design Rules* from *Design Principles* founded in *Design Guidelines. Design Guidelines (DGs)* are any useful text-based and/or illustrative information for understanding AM categories, processes, operating procedures and best practices. *DGs* offer best practices when using AM in product design to take advantage of the capabilities of a category of AM process. Most of the work reported in the literature in terms of benchmarking studies, experimental reports, and identification of errors and issues in AM fall in this area.

From the general *DGs*, specific design recommendations in terms of process-specific or material-specific trade-offs cannot be made. However, if certain *DGs* are consistently reported in the literature one can formulate appropriate general design principles. *Design Fundamentals (DFs)* are the basic components extracted from design guidelines and used to compose design principles and subsequent rules. They include elemental geometric features, geometry related parameters; material parameters and machine parameters.

Design Principles (*DPs*) are basic, logical correlations capturing process parameter and control parameters derived from *DGs* and corresponding *DFs* [36,37]. From *DPs* and associated formalisms, specific design rules can be formed. Design Rules (*DRs*) are prescriptive guidelines or explicit correlations that provide needed insight into manufacturability during design and process planning. *DRs* provide both experts and non-experts a way of making meaningful changes to part geometries without compromising manufacturability. Ultimately, *DRs* provide a means to constrain a design space, defining the boundaries of a design feature for a given process and material parameters.

DFs and *DPs* provide the opportunity to consistently develop *DRs*, so new knowledge can be formally and consistently encoded. Also, *DPs* provide the means enabling existing design rules reported in the literature to be suitably modified, extended, or reconfigured for supporting individual needs or promoting wider adoption. It is expected that the *GPR* approach will help to strategically identify best-practices, correlations between process parameters, process signatures, and product qualities to extract *DPs* to help derive *DRs* for all platforms of AM.

[2] https://www.americamakes.us/news-events/press-releases/item/950-america-makes-and-ansi-release-preliminary-final-draft-of-additive-manufacturing

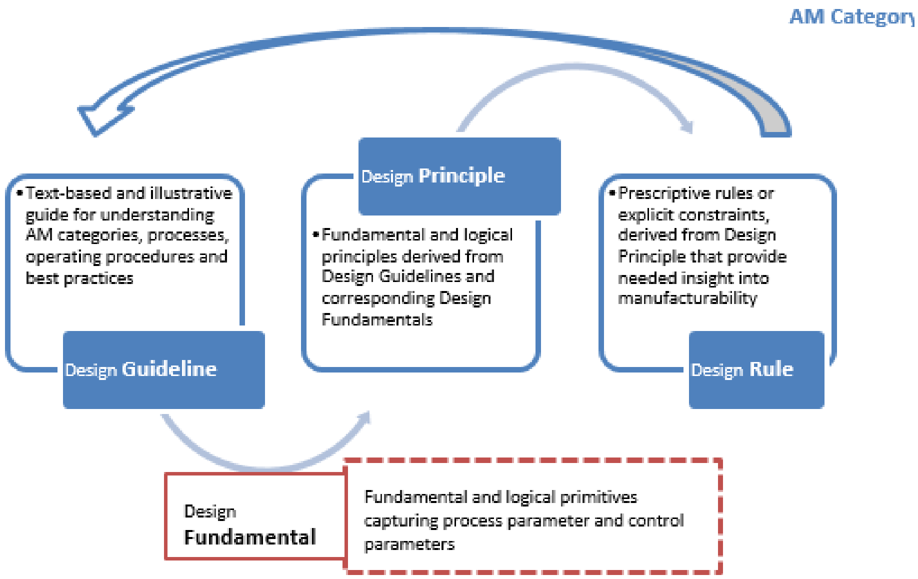

Figure 5 Guide-to-Principle-to-Rule Methodology

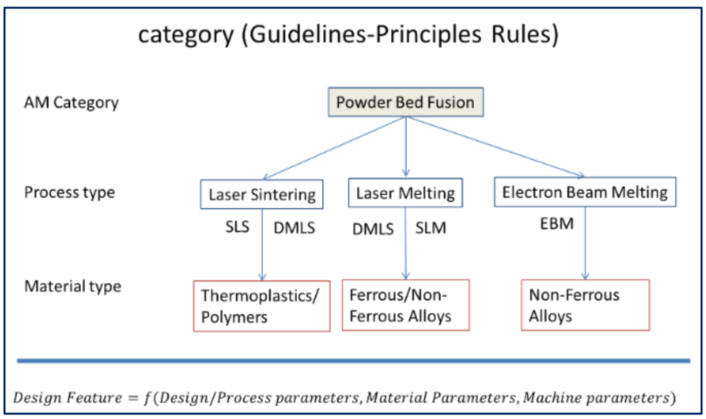

Figure 6 Category specific Guide-to-Principle-to-Rule

3.1. Basis for Design Rules - Features

In line with the *GPR* methodology, *DRs* can potentially improve design to process transitions through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to capabilities of AM technologies. As earlier mentioned, *DRs* are prescriptive guidelines that provide the needed insight into manufacturability during design and process planning. In this effort, we focus on *DRs* based on *DF*s derived from the literature. *DR*s can be established based on the capability of an AM process to build such *DF*s (e.g., geometrical features, mechanical features, or other elemental structures).

Table 1 lists categorized AM design features reported in the literature. The categories reflect observations from the literature review as well as basic AM concepts. Note that this list is not exhaustive.

Table 1 Design Features in the reported literature

Geometric features	Freeform surfaces	Pass-fail features	Mechanical features	Related Measurements
Cubes Hollow cubes Flat beam Cylindrical holes Solid cylinders Hollow cylinders Eclipse Spheres Cones Slots Holes Inclined Surface Overhangs Plates	Free flowing geometry Intricate Uniform Non-uniform	Thin walls Thin slots Slim cylinders Small holes	Fillet Chamfer Gaps Blend Bracket Cavities Bores	Surface roughness Accuracy Linear accuracy Flatness Straightness Parallelism Repeatability Roundness Cylindricity Concentricity Symmetry Taper Repeatability of radius

The following are the perceived benefits of deriving *DRs* based on *DFs*:

- Formalizing rules based on fundamentals is intuitive and can be based on the critical design parameters
- Relating part design to features (feature-based design) is well-conceived
- Relating process-machine influence to building fundamentals is widely reported
- Correlating fundamentals to desired process parameters setting and process signatures can be useful when developing expert systems
- Relating part quality based on feature-based measurements can be easily quantifiable
- Availability of literature on feature-based measurement for AM, e.g., benchmarking studies, design experiments is an advantage.

3.2. Formalization of the approach

3.2.1. Design Guideline (DG)

A successful AM build generally depends on the process related design parameters, material parameters, and the individual machine parameters. Process related design parameters include feature size, angles, accuracy, surface roughness, wall thickness, etc. Material parameters include powder size, distribution, flowability, etc. Machine parameters can include laser powder, scan speed, layer thickness, etc. A design guideline captures any or all of the relevant information about the parameters necessary for establishing process dependent and process independent relationships.

For example, *DG*: hollow cylinders should not be below the min wall thickness according to part orientation towards building platform.

3.2.2. Design Fundamental (DF)

Design Fundamentals can be abstracted from the design guidelines. They can be categorized as follows:

Features**; Geometry related parameters;** *Material Parameters*; ***Machine parameters***

Table 1 lists the fundamental features based on those reported in the literature. Table 2 lists different categories of Design Fundamentals common to AM processes.

Table 2. *Design Fundamentals* common to different AM processes.

Index No	Geometry(G)	Process/Machine (P)	Material (M)
1	Part dimension	Platform orientation	Type
2	Part location	Platform dimension	Thermal property
3	Part orientation	Platform location	Physical property
4	Part tessellation tolerance	Build power property	
5	Feature dimension	Build power type	
6	Feature location	Build tool scale	
7	Feature orientation	Build tool offset	
8	Feature shape	Build tool location	
9	Feature topology	Build tool speed	
10	Feature property	Build area	
11	Feature undercut angle	Build layer thickness	

3.2.3. Design Principle (DP)

Formalizing the aforementioned design guideline as a design principle can be as intuitive as representing it as function as follows,

$$\mathrm{DP}_{\mathrm{Feature}} = \mathrm{f}(\textbf{Geometry related parameters } (\mathbf{G}), \textit{Material Parameters}(M), \boldsymbol{Machine\ parameters}\ (\boldsymbol{P}))$$

$$\mathrm{DP}_{\mathrm{Feature}} = \mathrm{f}(\mathbf{d_1}, \boldsymbol{d_2} \ldots \mathbf{d_x}, m_1, m_1 \ldots m_{\mathrm{x}}, \boldsymbol{r_1}, \boldsymbol{r_2} \ldots \boldsymbol{r_x})$$

where $\mathbf{d_1}$ to $\mathbf{d_x}$, m_1 to m_{x}, $\boldsymbol{r_1}$ to $\boldsymbol{r_x}$ represents feature specific parameters.

Consider an example of a thin wall built using PBF process

$\mathrm{DP}_{\text{thin wall}} = \mathrm{f}(\mathbf{t}, \boldsymbol{\beta}, \mathbf{h}, z, f, \boldsymbol{P}, \boldsymbol{S}, \boldsymbol{t})$; If 90° ≥ **β** > 30°then **t** is 0.4 mm

If **β** = 30° then **t** is 0.3 mm for metal PBF process

In this example, t is the wall thickness, β is the orientation, h is the height, z is the powder size, f is the flowability of the powder, $\boldsymbol{P}$ is the laser power, $\boldsymbol{S}$ is the scan speed, $\boldsymbol{t}$ is the layer thickness. This basic correlation of design fundamentals serves as a basis for the development of rules for thin walls.

Specific values may depend on process, machine manufacturer, or user, but the basic premise supports the tailoring of customized rules.

3.2.4. Design Rule (DR)

Design rules are specific correlations that provide needed insight into manufacturability. For e.g., consider a design feature such as Hollow Cylinder to be built using a Powder Bed Fusion (PBF) process.

$$\mathrm{DR}_{\text{Hollow Cylinder}} = \mathrm{f}(\mathbf{d_1}_{\mathbf{a}}^{\mathbf{b}}, \mathbf{d_2}_{\mathbf{a}}^{\mathbf{b}}, \mathbf{d_3}_{\mathbf{a}}^{\mathbf{b}}, m_1, m_2, \boldsymbol{r_1}, \boldsymbol{r_2})$$

with the preferred value or range of values for $\mathbf{d_1}, \mathbf{d_2}, \mathbf{d_3}, m_1, m_2, \boldsymbol{r_1}, \boldsymbol{r_2}$ (range denoted by **a-b**) specific to PBF process.

It would benefit the AM community, if the preferred settings of control factors are identified based on specific *DF*s. Then, a specific *DR* will identify, for example, a laser beam offset and scaling value to improve the geometric accuracy of an artifact to be produced, providing insight into trade-offs that may be available.

3.2.5. Implementing the GPR approach

Based on observations across the published AM process literature, design guidelines, design fundamentals, principles, and rules and be captured at different levels of abstraction. At the highest level of abstraction guidelines, principles or rules can apply across process categories (i.e., process independent), and can be classified based on the *GPR* approach as a set (collection) of general guidelines, principles or rules that can be applied across processes.

$$DG = [dg_1, dg_2, dg_3 \dots dg_n]$$

$$DF = [df_1, df_2, df_3 \dots df_n]$$

$$DP = [dp_1, dp_2, dp_3 \dots dp_n]$$

$$DR = [dr_1, dr_2, dr_3 \dots dr_n]$$

At a second level of abstraction, guidelines, principles or rules that cannot be applied across process categories (i.e., process dependent), can be classified as a set of category specific guidelines, fundamentals, principles or rules.

$$cDG = [cdg_1, cdg_2, cdg_3 \dots cdg_n]$$

$$cDF = [cdf_1, cdf_2, cdf_3 \dots cdg_n]$$

$$cDP = [cdp_1, cdp_2, cdp_3 \dots cdp_n]$$

$$cDR = [cdr_1, cdr_2, cdr_3 \dots cdr_n]$$

In practice, general guidelines or category-specific guidelines are useful for reference and educational purposes; however, they are often ill-suited for direct implementation. Given the different AM categories and manufacturers, and even variations of machines from a single manufacturer, specific rules need to be created to capture the capabilities. The *GPR* approach provides a standard approach to construct specific, customized rules based on fundamentals such as shapes, sizes, hierarchical structures, and material compositions.

3.3. Examples from the Literature

Designing parts for PBF in general is similar to designing parts for injection molding or die-casting, but with inherent process differences. It is very important that these differences in terms of opportunities and constraints are captured. For example, PBF parts should have a minimum wall thickness of 0.040 inches (1.0 mm); holes in large blocks of material should be smaller than specified due to the shrinkage effect. Keeping wall thickness at 0.120 inches (3.0 mm) or less will minimize this effect [61].

4. CONCLUSIONS

This paper presents relevant efforts towards establishing developmental procedures for design rules for AM. The primary goal of the review is to offer insights into designing for AM and to extract fundamental principles for derivative rules based on general guidelines or best practices. Capturing explicit design rules can potentially lead to a breakthrough in design and process planning. Importantly, having a standard to capture such constraints and opportunities through design rules will broaden AM industrial applications. In line, we proposed a simple *Guide-to-Principle-to-Rule (GPR)* approach where we base the *Design Rules (DRs)* from *Design Principles (DPs)* in turn derived from *Design Guidelines (DGs) and corresponding Design Fundamental (DFs). DPs* provide the opportunity to consistently develop *DRs*, so new knowledge can be encoded formally and consistently. *DPs* also provide the means for existing design rules reported in the literature to be suitably modified, extended, or reconfigured to support individual needs or to promote wider adoption. We initially focus on *DRs* based on elemental Design Fundamentals (*DFs*) reported in the literature. Moving forward, based on some collaborative designed experiments, manufacturing restrictions for basic geometries can provide material specific *DP*s for designers in early stages of product design.

However, research is still required in understanding the design-to-manufacturing limitations and barriers like material cost, qualification, and certification, particularly for mission critical components, such as aerospace parts or automotive parts.

Future efforts in this direction could potentially include:

- Further categorizing *DGs*, *DFs*, *DPs*, and *DRs*
- *DRs* as the basis for expert systems
- Capture *DRs* for different metal-additive processes and materials
- *DRs* from best-practices captured from vendors and users
- *DRs* database easily extensible by user based on *DPs*
- *DGs* and *DPs* captured for emerging AM processes and materials
- Specialized design rules may be desired to satisfy a new process, to incorporate new knowledge, or to develop in-house applications.

DGs and *DPs* provide a solid foundation on which application-specific rules can be derived and disseminated as new data and information becomes available.

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