OVERVIEW OF THE DEVELOPMENT AND ENFORCEMENT OF PROCESS-DRIVEN MANUFACTURABILITY CONSTRAINTS IN PRODUCT DESIGN

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ABSTRACT
Design-for-manufacturing (DFM) concepts have traditionally focused on design simplification; this is highly effective for relatively simple, mass-produced products, but tends to be too restrictive for more complex designs. Effort in recent decades has focused on creating methods for generating and imposing specific, process-derived technical manufacturability constraints for some common problems. This paper presents an overview of the problem and its design implications, a discussion of the nature of the manufacturability constraints, and a survey of the existing approaches and methods for generating/enforcing the minimally-restrictive manufacturability constraints within several design domains. Four major design perspectives were included in the study, including the system design (top-down), the product design (bottom-up), the manufacturing process-dominant approach (specific process required), and the part-redesign approach. Manufacturability constraints within four design levels were explored as well, ranging from macro-scale to sub-micro-scale design. Very little previous work was found in many areas, but it is clear from the existing literature that the problem and a general solution to it are very important to explore further in future DFM and design automation work.

1 INTRODUCTION
Manufacturing is a fundamental step in the design cycle of every product, one that is often overlooked in the early phases of design formulation and requirements definition. It is common for the process selection to be done after the finalization of the design, speeding up the work but adding risk [1–3]. If there is a mismatch between the final design and available manufacturing processes, the design may need to be sent back for additional iterations, delaying completion and increasing the schedule and cost risk [4–7]. If the final product is relatively simple or a tried-and-true basic design that was previously developed, the manufacturing is usually very straightforward, and the risk is low. However, for more complex designs (such as those created using algorithms, e.g., topology optimization or generative design), it is possible for final designs to be completely unmanufacturable with any of the available processes [8–10]. In the worst case, the design process may need to be reversed several steps or started over to incorporate the new lessons learned by the design team during the manufacturing attempt (Figure 1). This is not dependent on any particular lifecycle design method [1,5,8] and could be applicable for a linear model (Figure 1) as well as agile [11], evolutionary [12,13], and iterative models [14], as well as others.

To address this in part, design-for-manufacturing (DFM) principles have been developed in recent decades [8,15–17]. As a technical approach, DFM has commonly referred to a set of design heuristics in which the design is simplified as much as possible to reduce the risk of mismatch with a manufacturing process and risk to the budget and schedule of the product development. There traditionally have been a wide variety of these rules, which can be summarized as five basic guidelines [7,8,18,19]:

- Make the design as simple as possible
- Use common, cheap, and easy-to-process materials
- Use as many standard components as possible in a system
- Make the tolerances as liberal as possible, except when they can be effectively allocated without large trade-offs
- Consult manufacturing personnel for design decisions

FIGURE 1: Manufacturability check and potential loop-back when design is mismatched with manufacturing process

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The most important characteristic of these rules is that they are process- and material-independent and are typically very generic [8, 15, 20]. This version of DFM is extremely effective in a mass-production environment with simple or established designs, but tends to be overly-restrictive for specialized or complex designs and results in designs favoring simplicity over optimality [8, 21, 22]. In a mass-customization paradigm, such as the one emerging in recent years [23–25], it is vital for designers to fully utilize the design space and optimize the design as much as possible [26–29]. This is especially important when producing small-batch, customized, high-value parts such as those needed for aircraft and medical devices. Therefore, a DFM technique which would restrict the design space only enough to guarantee manufacturability is needed. To ensure the minimum restriction on the design space, it is necessary to replace the general heuristics with well-defined constraints driven directly by the characteristics of the processes or methods selected.

With this in mind, any manufacturing process can be said to be subject to a set of natural manufacturing constraints which affect its use domain and which must be considered in the design process to achieve a design that is both ideal and manufacturable. In addition, it is necessary to consider manufacturability constraints, which are on the design itself and are in response to the manufacturing constraints. For example, a machined aluminum part design would be constrained by the tool size, speed, and cutting rate of the mill [30] (manufacturing constraints) and a minimum feature size to ensure that the part could dissipate the heat and force of machining without warping [34, 35] (manufacturability constraint). The design “ownership” in each domain is different, with production engineers best understanding the manufacturing constraints. This requires excellent communication between the production team and the designers, a task that is not always performed effectively [3, 8, 10, 15, 16]. More general mapping approaches have been suggested for translating manufacturing constraints directly into manufacturability constraints [5, 9, 31], but this is an immature area and needs much additional research.

It should be noted that, while both the manufacturing and manufacturability constraints need to be considered during design, designers do not have the same level of control for each. The manufacturing constraints are natural and inherent in the process itself, and therefore typically not controllable beyond developing new processes or selecting one with acceptable limitations [8, 30, 36]. The manufacturability constraints, on the other hand, are driven by the manufacturing constraints, but also allow the designer to modify or control their magnitude. In mathematical terms, the manufacturing constraints are generally equality constraints (fixed value) and the manufacturability constraints are inequality (boundary) constraints. With this in mind, it should be noted also that the manufacturability constraints are more likely to be continuous functions (e.g., the range of wall thicknesses on a cast part), while the manufacturing constraints are more likely to take the form of combinatorial or discrete functions (e.g., a list of cutting tool sizes for a milling process). Showing that the manufacturability constraints are not violated for a particular design (via heuristic or monotonicity analysis, or other methods) is a good proof that the design is likely manufacturable without needing to use DFM to restrict the design space.

The purpose of the work presented here was to survey the existing DFM literature to find the state-of-the-art for the definition of the manufacturing constraints, and the generation and enforcement of the manufacturability constraints. An extensive search was performed in important design and manufacturing journals, conference proceedings, and searches in Scopus, Web of Science, and Google Scholar. Note that this is a design-practice focused survey and not a formal, systematic review paper. This work is structured into several sections, plus discussion and conclusions:

- **Section 2**: An overview of manufacturing processes and their natural constraints
- **Section 3**: Overview of DFM impact on several approaches, focusing on system-level (top-down) design, product-level (bottoms-up) design, the case where a specific manufacturing process is required, and part-redesign
- **Section 4**: DFM level analysis at several design levels ranging from macro-level to sub-micro-level considerations

### 2 PROCESSES AND MFG CONSTRAINTS

Most standard (non-hybrid) manufacturing processes fall into one of three major families, namely subtractive, additive, and formative (Figure 2) [30]. There are numerous finishing, as-

![FIGURE 2: Example domain applicability for formative, subtractive, and additive manufacturing processes relative to manufacturing cost and available design complexity](image-url)
FIGURE 3: Design-related process characteristics for SM, AM, and FM, shown with examples of common processes and common manufacturing constraints for processes within each domain

In general, SM processes tend to have the most restriction on the types of part features that can be created due to the essential requirement that cutting tools be able to reach all of the part from some force point (commonly a rotating spindle) [52–54]. AM, by definition, does not have tooling-related complexity restrictions, but there are some restrictions due to support material removal [55, 56], natural material anisotropy [57, 58], and process mechanics [42, 43]; however, the possible design complexity is very high for most of the AM processes [42, 43, 59]. Conversely, FM is almost entirely dependent on the tooling used and is limited to the tooling complexity. In the most common case, the tooling (molds, forging tools, and similar) must be made using some SM process, which limits its complexity to that which can be cut or machined [30, 48–51]. However, some FM processes can use free-form or shell molds (for example, investment casting) which dramatically enhances the possible part complexity [36, 60–62].

Of the three major domains, AM has the widest range of available materials when all of the major families are considered; the various AM processes can use almost any material which can somehow be applied in a layer and fused with a previous layer [42, 43, 63]. AM materials are most commonly in the form of filament, resin, or powder, but may be as diverse as water (ice prototyping [64]) or rolled metal sheets (ultrasonic consolidation [65]). In general, SM materials are limited to those which can easily be cut with a tool and can tolerate the associated heat load, usually ductile metals and hard polymers [30, 36]. On the other hand, FM materials are limited to those that can be stably melted or cold-formed to conform with some tooling [30, 48, 50]. This is less restrictive than SM, being able to process various bulk and molten materials, resins, and metal powders, but less free than AM because of the dependence on tooling.

Due to the need only for standard clamps and fixtures [30, 36, 39] for single parts, SM tends to be able to produce one-off parts relatively cheaply compared to AM and FM. However, it can be more expensive to mass-produce parts using SM because of the need for the special fixtures, jigs, and higher quality cutting tools than needed for one-off parts [30, 36]. The cost for one-off AM parts is high due to the expensive nature of the processing
equipment and materials, as well as the generally slow processing speed; unlike SM, AM can be relatively cheaper to perform mass production for some (not all) complex designs since the manufacturing time and cost is mostly dependent on total part volume and not complexity [43, 66]. The supply chain for AM, within the available set of processes and materials, is also often more efficient and less prone to blockages [42, 43]. Finally, FM is very expensive for single parts and very cheap for mass production, making it ideal for many products. The reason for the high up-front cost is the tooling initial cost, but this goes down dramatically as the tool is used more [30, 36]; the raw materials for FM are generally much cheaper than those for SM and AM (since they will be formed or melted during processing, high quality finish and precision in the materials is usually not necessary), the supply chain is very efficient, and one good set of tooling may last for hundreds of thousands of parts [30, 50, 51].

3 MANUFACTURABILITY CONSTRAINTS: DESIGN APPROACH PERSPECTIVES

In the preceding section, the three major classes of manufacturing processes and their common constraints were explored. Careful consideration of these constraints and their potential impact on design allows the development of customized DFM approaches for specific problems; this, in turn, allows the designer to restrict the available design space just enough to ensure manufacturability. This section examines the various specific DFM methodologies developed within four essential design perspectives in which DFM has been applied effectively. These are (1) the system design (top-down) perspective, (2) the product design (bottom-up) perspective, (3) the case where a specific manufacturing process is required, and (4) the part-redesign perspective.

3.1 System Design (Top-Down) Perspective

In the system design (top-down) design perspective, the goal of design is to consider the construction of a system or subsystem and is less concerned with the optimal design of individual parts; while optimization of each part is important, it is more important in top-down design for each part of the system to be optimal relative to overall system utility [2, 6, 67]. From the DFM perspective, the focus will be to make the manufacturing process selection such that the parts are manufacturable in an efficient way, and such that the materials and tolerances are compatible. The business case for considering a DFM technique is easy to make, as it prevents re-design and resulting delays, as well as ensuring the the possible design space is as large as possible [5, 68–70].

The most obvious application of within this domain is the improvement of any general lifecycle design technique, such as those proposed by NASA [1], INCOSE [67], Pahl et al. [6], and Blanchard & Fabrycky [2]. Within such a design engine, the more general DFM approaches usually are applicable, allowing either the use of DFM and the optimal selection of manufacturing processes after design is completed [8, 16]. While the general engine does not necessarily need customized DFM methods (especially if the design is very simple), when the lifecycle design approach is applied to a particular domain, the use of minimal-DFM can be very valuable.

This value can be especially apparent in previous work done on aircraft design. Generally, aircraft parts have very tight tolerances, need to be very lightweight, and need to be highly consistent, which dramatically limits the available manufacturing processes for these parts [68, 69, 71]. The set-based concurrent design technique proposed by Vallhagen et al. [71] uses a type of custom DFM technique to eliminate clearly infeasible manufacturing processes early in the design and allows the accommodation of process constraints at several points in the lifecycle. A similar approach focused on ensuring that all of the parts have compatible tolerances and that the various system interfaces are producible was developed by Barbosa & Carvalho [69].

Electronics and mechatronics design is an important application of DFM at the system level. The 2003 study by Bajaj et al. [72] explored this in detail, developing a rule-based system for finding and imposing the relevant constraints (of several options available from the system to the designer) to accomplish a good quality design. Several studies by W.H. Wood [73, 74], Shetty et al. [75], and Berselli et al. [76] discussed some of the major issues when designing mechatronic systems and presented a framework for considering formal (mathematical) and heuristic manufacturability constraints related to both the mechanical and electronics sides of the design.

3.2 General Product Design (Bottom-Up) Perspective

The design perspective with the most direct benefit from the use of minimally-restrictive DFM is design of individual parts. When the design focus is bottom-up (i.e. the system is built from several products individually developed) and each part must be optimized individually, the largest possible expansion of the design space is needed. It is assumed in this case that a specific manufacturing process has not been required by the customer and the designer is free to select the one that provides the least restrictive manufacturing profile and design space.

In most of the DFM studies found on part design, a specific manufacturing process was defined in the problem statement and so it was not true bottom-up design (where it is assumed that performance is the primary goal and several production processes may be possible) [77, 78]; these cases will be discussed in the proceeding section. The work found in this area was primarily in the domain of decision analysis, where the manufacturability requirements or guidelines are discovered and fed back into the design process as it developed. Works by Barnawal et al. [20] and Budinoff et al. [79] analyzed this in detail, showing that effective communication of the constraints and manufacturing expectations was the key to ensuring product manufacturability; this was shown to be true for both heuristic, experienced-based constraints and formal mathematical manufacturability constraints.

A large and detailed case study on the mathematical definition and enforcement of manufacturability constraints was completed by Iyengar & Bar-Cohen [80] in which a side-inlet-side-exit (SISE) parallel plate heat exchanger was developed constrained for eight different processes (extrusion, two types of die casting, bonding, folding, forging, skiving, and machining); it was found that feasible solutions for the design existed under each process constraint set, but the constraints were clearly active and provided very different optimal solutions based on the process selected. Similarly, several studies by Vatanabe et al. [9],
Guest & Zhu [81], Mantovani et al. [82], Zuo et al. [83], and Reddy et al. [84] have examined the impact of manufacturability constraints on topology optimization (TO) solutions for several different manufacturing processes simultaneously, with results similar to the heat exchanger problem described above. Since TO is an algorithm-based design process, the manufacturability constraints are usually enforced inside of the algorithm. For example, the study by Vatanabe et al. applied manufacturability constraints for six different processes (casting, milling, turning, extrusion, rolling, and forging), producing a variety of different topologies under these constraints. The constraints were enforced in the form of topology constraints, such as minimum feature sizes, symmetry, and avoiding undercuts, within the mathematical formulation of the problem.

3.3 Manufacturing Process Perspective

This section continues the discussion from the previous section on product design, with a manufacturing process specified.

3.3.1 SM Processes

In general, machining requires a careful tool-path planning to ensure that all of the geometry can be cut with the tools [85]; this is true for both manual and computer-controlled machines. For example, Monge et al. [86] proposed a three-step process for designing turbine blades by generating an optimal shape based on a combined set of constraints from a computation fluid dynamics (CFD) model and an optimal toolpath generator; the solution found produced both an improved design and one that was manufacturable using a machining process. More general solutions were developed by Kang et al. [87], Deja & Siemiatkowski [88], and Gupta & Nau [89], which are based on feature clustering and checking the optimality of a series of cutting path plans which open the design space as much as possible. In addition to path planning for conventionally-designed parts, machining constraints have been developed for use in TO-generated designs as well. Projection-based TO can be very effectively constrained for machining, as it is based on continuous geometric constraints and interfaces well with a toolpath, as shown by Guest & Zhu [81]. Specific machining and milling-related constraints have also been developed for a few cases within the level-set TO approach [90,91], as well as heavyside projection, gradient, and hybrid methods [83,92].

3.3.2 AM Processes

Most of the work done so far in establishing and enforcing manufacturability constraints for AM processes has been for the development of design rules, some for general AM and some for specific processes. The focus of extensive studies by Jee & Witherell [93], Adam & Zimmer [94,95], Bin Maidin et al. [96], and Kranz et al. [97] was on the development of standardized feature databases in which the AM manufacturing constraints could be applied to standard common part features to ensure manufacturability. The designer could then select the features from the database that are best for the design at hand while ensuring manufacturability. In a more focused effort, Tang et al. [98] presented a method for developing a unit structure-performance database to allow discrete optimization of light-weight housings via selective laser melting; this technique for arranging small standard features to optimize a design is useful and complementary with the feature catalogs developed in the previously-mentioned works.

Using the results from an extensive literature survey, Pradel et al. [99] proposed a framework for mapping of AM process knowledge for product design. They describe the need for more “practical” application of AM in design and suggest several methods for achieving this for general processes. Some work has been performed to establish AM constraints in TO [100,101], similar to those discussed in the previous section, but this is still an immature area and needs additional attention. Design rules and constraints for specific AM process have been proposed by several scholars. Thompson et al. [56] point out that many of the process limitations in AM come from the modeling and software used to drive the processes, but that this is an area where progress is being made.

In addition to more general AM constraints (minimal feature size [102], overhangs [55], surface roughness, avoidance of stress concentrations [58], material anisotropy [57], support material removal [103], among other things), some processes have more specific constraints which must be considered. While many of these are not well characterized, a lot of work has been done for some of the very common processes. For example, Utley et al. [104], Thomas [105], and Kranz & Herzog [97] proposed a series of manufacturability constraints for the selective laser melting (SLM) process directly driven by the process characteristics. These SLM constraints are things such as delamination, heat deformation, potential oxidation between the material layers, and scan pattern constraints specific to laser scanning processes such as SLM. Similar work has been done for selective laser sintering (SLS) [106,107] and electron beam melting (EBM) [108–110], which have similar manufacturing constraints, with EBM generally being less restrictive than SLS/SLM due to the use of a heated chamber.

Other specific processes for which process-specific design rules have been developed include fused deposition modeling (FDM) [111–113], stereolithography (SLA) [114,115], material jetting [116], and binder jetting [117]. The general design limitations cited from FDM are in the area of minimal feature size (more strict than standard AM constraints), support material design, and surface accuracy and finish. FDM, material jetting, and SLA have similar manufacturability constraints, with the exception that SLA and material jetting have less strict minimal feature size restrictions. Binder jetting, which uses powder as the raw material, has constraints similar to those of the powder bed processes (SLM, SLS, EBM) mentioned above except for those related to heat warping.

3.3.3 FM Processes

An area of significant interest in minimally-restrictive DFM has been in the use of casting processes to fabricate complex geometry generated by topology optimization (TO) algorithms. In the major studies reviewed, this is done by mapping the major casting/FM constraints [118] into the design within level-set [119,120], gradient [121], and projection [9,81,122] methods to generate a topology that is castable. Casting constraints are well-developed for TO, since they are much less strict than those for machining processes, and can be defined simply in terms of thickness and a requirement that the geometry be continuous; these constraints ensure that the liq-
uefied material can flow into the mold and reach all features, can dissipate the heat, and that a parting line can be established.

Some work has also been completed on the TO-based design of parts to be fabricated using an extrusion or drawing process. The manufacturability constraints for extrusion are much more simple than those for casting. When using a projection-based TO method, as done by Vatanabe et al. [9], the constraints are simply applied to a “slice” of the part; the domain is automatically continuous in an extrusion process, so the manufacturability constraints consist mainly of avoiding features that are too delicate to survive being pushed or drawn through a die. Li et al. [123] and Sutradhar et al. [10] showed that this can also be done using a type of internal projection within a level-set TO method.

In addition to DFM-based TO solutions in casting and extrusion, some work has gone into finding conventional (non-TO) design rules for closed-tooling processes, particularly injection molding, die casting, and powder metallurgy. Injection molding is typically limited to plastics (e.g., ABS or silicone), die casting to ductile metals (e.g., zinc or aluminum), and powder metallurgy to metal powder (sometimes mixed with a binder); manufacturability analysis within the appropriate tooling is focused primarily on being able to quickly and efficiently fill the mold with material and eject it safely. The manufacturability constraints then are in the form of feature restrictions (they must fit into and be easily removable from the tool), usually with a two-part tool, and the location of the tool parting line [124–127]. Powder metallurgy is the least restrictive [30, 128], as it can sometimes use a four-part tool instead of the standard two-part used in injection molding and die casting. Extensive work has gone into simulation of these processes in order to better understand how the material can flow into the tool and solidify in the way intended by the designer [129–133]; these simulations can be used to guide designs but generally are used just to check manufacturability and plan the process after the completion of the design.

3.4 Part-Redesign Perspective

From the perspective of green manufacturing, the primary value of the use of manufacturability constraints (besides the prevention of inefficient design and manufacturing) is in the area of re-design. Parts subjected to re-design are generally technically manufacturable but the designer has identified areas of improvement in the manufacturing or assembly. The redesign of parts specifically to make them more efficient or less expensive to manufacture was the subject of several studies for milled [134, 135], turned [136], and stamped [137] parts, as well as the production of part families [138]. While not technically DFM, this redesign approach is interesting as it shows a need for tightening manufacturability constraints once problems or inefficiencies are discovered after completion of the design. These problems could have been avoided by using proper DFM during original design, eliminating the need for corrective action later.

4 MANUFACTURABILITY CONSTRAINTS: DESIGN LEVEL PERSPECTIVES

The design of features and part details can be completed at different design levels, each of which requires different kinds of manufacturability constraints. The main difference, from a design perspective, of each of the levels is the feature size created within each domain. The macro-level is defined as containing features at least a millimeter in size, while meso-level features may range from a few hundred micrometers to one millimeter, the micro-level may range from one to a few hundred micrometers, and sub-micro-scale is less than one micrometer in size.

4.1 Macro-Level Design

One of the major tasks when designing at this level is the generation and refinement of macro-level structures and aggregates such as lattices, overhangs, mounting bosses, and similar features. Design at this level is generally straightforward, and is usually done using design rules and feature catalogs which provide manufacturable features. Definition of these rules for most traditional manufacturing processes (such as machining and injection molding) is based on simple DFM principles, as discussed in depth in Sections 3.2 and 3.3. Figure 4a shows an injection-molding caliper case, which is an example of a standard product with macro-scale features.

Fabrication of macro-scale features for AM processes is more complex due to the layered nature of the resulting material and the presence of natural voids, stress concentrations, and residual stresses [58, 141]. While it is important to use feature catalogs and feature families, the manufacturability constraints will be more strict than they would for more simple processes. Research has been performed specifically for AM processes; for example, the studies by Adam & Zimmer [94,95] and Bin Maidin et al. [96] developed a list of macro-level standard design features and their transitions. The rules presented are developed for several specific AM processes and incorporate process knowledge directly from these processes into the design of edges, wall thicknesses, gap heights, and other design features. Some AM processes (such as SLM) require the ability of the material to transfer heat rapidly during processing and small features need to be adjusted for this, including controlling the porosity [142]. Maximum length scale constraints for structural and fluid topology optimization is another important application; it can limit the size flow channels and structural members as needed, as shown by Guest [143] and Lazorov & Wang [144].

4.2 Meso-Level Design

The primary applications found for meso-level design were in the design of meso-scale features which act like a controllably-anisotropic material. Since, in most cases, the material for parts made using SM and FD process is approximately isotropic, this design level has been applied mainly to additively-fabricated parts. The use of AM to design and build meso-level materials structures was explore by several studies; Chu et al. [145], Yu et al. [146], and Garcia et al. [147] developed a theoretical framework for single- and multi-material problems, while Sivapuram et al. [148], Gopsill et al. [149], and Gardan et al. [150] explored the practical implications and requirements for using AM to build meso-scale tailored materials. Examples of some AM-generated mesostructured materials are shown in Figure 4b.

4.3 Micro-Level Design

Manufacturing constraints derived for micro-scale features and parts (Figure 4c) could be more restrictive than larger-scale
designs due to the small size of the dimensions. Most conventional manufacturing processes, including casting, forging, machining, and additive manufacturing, do not have the capacity to fabricate extremely small geometry; therefore, it is vital that a production process be selected and considered in the design stage to make sure the final product is manufacturable.

The small number of manufacturing processes that can reliably fabricate at the micro-scale have been reviewed, so the capabilities if these processes are known and can be used to generate manufacturability constraints. For example, Ashman & Kandlikar [151] examined several types of manufacturing processes for fabricating heat exchangers with hydraulic diameter of less than 200 micrometers. Etsion [152] presented a comprehensive review on micro-level laser surface texturing (LST) in connection with hydrodynamic lubrication and wear reduction as well as surface texturing in general. Romig et al. [153] discussed issues of micro-electro-mechanical systems (MEMS) design and fabrication in various aspects, including materials, manufacturability, performance, and reliability. AM-based fabrication has been discussed by Frazier et al. [154] and Dede et al. [155]; while AM offers great potential for this, there are clear problems with the processes that need to be addressed before they can be effectively used for micro-scale fabrication. These include material defects, anisotropic properties (which affect the fabrication more for smaller geometries), inconsistent cooling, residual stresses, complex material behavior, and other related concerns. In addition to feature size restrictions, the topologies and shapes also should have specific constraints in order to be fabricated at this scale. Considering a micro-milling process with a ball end mill, Lee et al. [156] applied a spline-interpolated smooth free surface with a maximum slope angle as a manufacturability constraint in the surface texture design-for-lubrication problem. Even though the target design size is larger than micro-level, features in the design may still be smaller than those which can be fabricated at this level by certain processes. Specifically, keeping the feature size larger than the manufacturing resolution should not be overlooked in topology and shape optimization. Sigmund [157, 158] showed examples of manufacturing failure due to feature size, and introduced robust topology optimization frameworks that can filter out infeasibly small features.

4.4 Sub-Micro-Level Design

While the micro-scale design and fabrication of parts and features is very challenging, accomplishing it at the sub-micro-scale is even more restrictive and difficult. However, this is an extremely important design scale and many important applications demand features at this size. Examples include friction and wear reduction [159, 160], nano-electro-mechanical systems (NEMS) [161], and superhydrophobic surfaces [162]. These design features are typically part of larger-scale parts and assemblies, and may require additional manufacturability constraints compared to those established elsewhere in the design. Sub-micro-level surface treatment using micro- and nano-texturing and surface modification strategies are similar to those discussed in previous sections, except that the tolerances are much tighter and the manufacturability constraints are very restrictive. Sub-micro-scale surface texturing and treatment methods for corrosion and wear resistance often involve combinations of thermal, electrochemical, and mechanical processes, which alter surface electrochemical and molecular properties, mechanical shapes and patterns, or sometimes material itself by applying coatings [163]. Often, sub-micro-level features and parts are manufactured using the same or similar techniques that are applied to fabricated nano-scale structures; these fabrication techniques can be typically classified into two categories: top-down and bottom-up approaches.

Top-down fabrication approaches mostly utilize nanolithography, deposition, and etching processes. Conventionally, this approach is used in the semiconductor industries, but the usage is expanding to more intricated applications, including NEMS, sensors and actuators, optoelectronics, as it is capable of fabricating structures down to nanometer resolution [161]. Due to the layered nature of fabrication processes, the top-down approach is mainly limited to 2D or 2.5D structures in manufacturability. Structures can be fabricated by repeated material deposition and removal processes, supporting very accurate manufacturing, but presenting manufacturability problems when the length scale is less than a few nanometers [164, 165]. The bottom-up approach places material at the desired locations, similar to 3-D printing processes. Currently, a direct-write nano-deposition (specifically, two-photon polymerization, 2PP) method is avail-

FIGURE 4: Examples of design features at various levels. (a) macro-scale injection-molded caliper case, (b) meso-scale 3-D printed thin-walled structures, (c) micro-scale electrodes [139], and (d) sub-micro-scale LED pits [140]
able to fabricate structures smaller than the micrometer level easily, and at its limits down to a length scale of approximately 50 nm [166, 167]. This approach has similar characteristics and constraints to what is commonly seen in 3D printing; however, even with the wide freedom in shape and topologies that AM enables, postprocessing of structures fabricated using nanoscale AM via 2PP is still challenging. The main challenge is the removal of support structure and any extra raw material, as this is very difficult or impossible when dealing with extremely small parts [168].

5 CONCLUSIONS AND FUTURE WORK

The purpose of this work was the explore the generation and imposition of process-driven manufacturability constraints for product design problems. First, a description of the problem was presented, showing that many designs require the use of manufacturability constraints as a strategy to take advantage of the largest possible design space. Next, the various major manufacturing processes and their common manufacturing constraints were discussed in depth. After discussion of the manufacturing constraints, the design literature was explored from several different perspectives and levels for existing approaches in applying process-driven manufacturability constraints to design problems. Four different design perspectives were examined; first from the perspective of system-based design, then product-level design for both the general case and the case where a manufacturing process is specified, and finally from the perspective of part re-design to address manufacturability problems. Four different design levels or scales were analyzed, ranging from standard macro-scale design to sub-micro-scale problems.

This work focused on design under single, non-hybrid manufacturing processes that are standardized and with which most designers should be familiar; joining processes (such as welding) and secondary manufacturing (i.e., the production of manufacturing tools) were not considered, as they were beyond the scope of this work and are deserving of their own in-depth reviews. The design and fabrication of material microstructure were also not addressed in the present study, as numerous other works have explored it in great depth. A new field of part redesign for emerging technologies (instead of redesign to address manufacturability problems) has been developing over the past several years, but is not yet mature and was not examined in this work.

Some important observations and conclusions were made after reviewing the collected literature on the topic:

- A formal, generic method for mapping manufacturability constraints from any manufacturing process to any design problem does not yet exist, but much progress has been made for some specific problems.
- Parts conventionally-designed (i.e., not designed using an algorithm) under several common FM and SM processes do not appear to have formally-defined methods for ensuring manufacturability of the parts beyond visual observation and rules-of-thumb. Especially noted were investment casting, blanking/coining/stamping, turning/facing processes, rolling, and forging processes.
- The design of conventional sand and shell casting parts seem to be completed using mainly heuristic-based design and traditional DFM principles (i.e., "make it simple").
- In top-down (system-level) design, the manufacturability constraints need to consider global as well as local manufacturability problems.
- In bottom-up (product) design, the same product can have vastly different final designs from the same starting point when active manufacturability constraints for different processes are considered.
- The established manufacturability constraints for SM processes tend to be related to surface topology, while AM constraints generally relate to part cross-section and material behavior, and FM constraints seem to be driven primarily by material behavior when interacting with and being removed from the tooling.
- Part re-design solutions presented in the literature to address manufacturability problems show that a simple and effective way to address manufacturing problems is to tighten the manufacturability constraints for the design.
- If it can be shown that all the manufacturability constraints are inactive, it is very likely that the design is manufacturable without the constraints.
- The smaller the design scale, the more restrictive the manufacturability constraints become and the fewer process types are capable of fabrication.

Future work should focus on addressing the areas where minimally-restrictive manufacturability constraints are not in regular use, as they can help to open up the design space and allow the further optimization of the design. There is a great need for a standardized (whether formally-standardized or in common use) method for mapping the manufacturability constraints directly to design constraints. If this can be developed and automated, it could dramatically speed up the design process and increase its reliability for new areas of design exploration.

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