THE NEED FOR EFFECTIVE DESIGN GUIDES IN ADDITIVE MANUFACTURING

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Abstract

As interest in additive manufacturing (AM) grows, design guides are needed for helping designers conceptualize and embody products that are suitable for AM. As these guides begin to emerge, they are focused primarily on the limitations of AM, including the types of features that can and cannot be built with a particular process and the dimensional limitations on those features. To design for AM effectively, however, designers need guides that help them understand not only the limitations of a particular AM process but also the design opportunities and freedoms afforded by the process. Furthermore, developing a basic understanding of the AM process and its relationship to those limitations and capabilities helps designers translate their knowledge to new applications. An expanded type of design guide is needed that fulfills all of these functions for the designer.

Keywords: Design for Additive Manufacturing (DfAM), Design for X (DfX), Design education

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1 INTRODUCTION

Designers need comprehensive practical knowledge of a manufacturing process in order to design parts that are not only feasible to fabricate but also economical and reliable. This need is just as acute for emerging additive manufacturing processes as for conventional subtractive or forming processes. Although the popular press often describes additive manufacturing (or 3D printing, as it is popularly known) as a technology for quickly fabricating almost anything in almost any location, this claim is misleading. Novice users of additive manufacturing (AM) quickly discover that a specific AM technology may afford unprecedented three-dimensional design freedoms but that those freedoms must be balanced with significant restrictions on the types of features that can be built.

Accordingly, there is a growing need for effective design guides for particular AM technologies. The general purpose of most design-for-manufacturing guides is to avoid the over-the-wall type of product development process in which (1) parts are designed, (2) transferred to manufacturing specialists who identify all of the ways in which it is either impossible or expensive to manufacture, and then (3) transferred back to the engineer to revise the designs in a very time-consuming and expensive iterative loop. In the AM context, in which the lack of part-specific tooling enables much more rapid and less expensive experimentation, the designer himself/herself often tries and fails to build a new part multiple times before getting it just right. In this context, engineers often create AM design guides to help designers avoid common failures in their own builds and build their parts right the first time.

The difficulty with designer guides that evolve from this design-build-fail-redesign-rebuild context is that they focus almost entirely on mistakes to be avoided. They tell designers what **not** to do to avoid failed builds, but they do not help designers create parts that leverage all of the unique freedoms of AM and build a business case for utilizing AM in the first place. Effective design guides need to do all of these things.

This paper outlines some of the essential components for an effective AM design guide. As a means of focusing the discussion, the examples focus on powder bed fusion (PBF), also known as selective laser sintering, but the general discussion is applicable to other AM processes, as well. The next section of the paper is a review of available design guides for PBF, which focus primarily on design constraints. The following section suggests other important components for effective AM design guides and explains why they are important for the AM designer.

2 A REVIEW OF EXISTING DESIGN GUIDES FOR POWDER BED FUSION

Numerous design guides are available for powder bed fusion (PBF) of plastic or metal parts. Some of the design guides are generated by machine manufacturers such as EOS (EOS GmbH, 2012; EOS GmbH, 2015). Others are generated by consultants and service bureaus that fabricate parts on demand (Quickparts (3D Systems), n.d.; Crucible Design Ltd., 2014; Crucible Design Ltd., 2015; Stratasys Direct Manufacturing, 2016). Academic researchers also generate design guidelines for PBF, often based on systematic studies of test parts (e.g., (Samperi, 2014; Seepersad, et al., 2012; Kranz, et al., 2015; Adam and Zimmer, 2014; Yang and Anam, 2014)).

The overwhelming majority of published guidelines describe limitations on feature types, geometries, and dimensions. Since PBF fabricates parts by selectively sintering or melting powders with a laser, the laser spot size, the layer thickness, the mean size of the powder particles, and the thermal environment in the build chamber work together to limit the minimum size of many features including thin walls and small rods, holes, and slots. An example design guideline focused on minimum feature size is illustrated in Figures 1 and 2. Since the powder bed supports parts as they are being built, it is possible (at least with polymer PBF) to build assemblies of parts, but minimum clearances between moving parts must be maintained to prevent fusion during the build. Letters resolve better when they are recessed rather than raised and drawn in a sans serif font with at least a minimum font size (typically at least 14 point, but sometimes higher). Finally, specific machines with fixed build chambers place restrictions on the maximum size of a part.

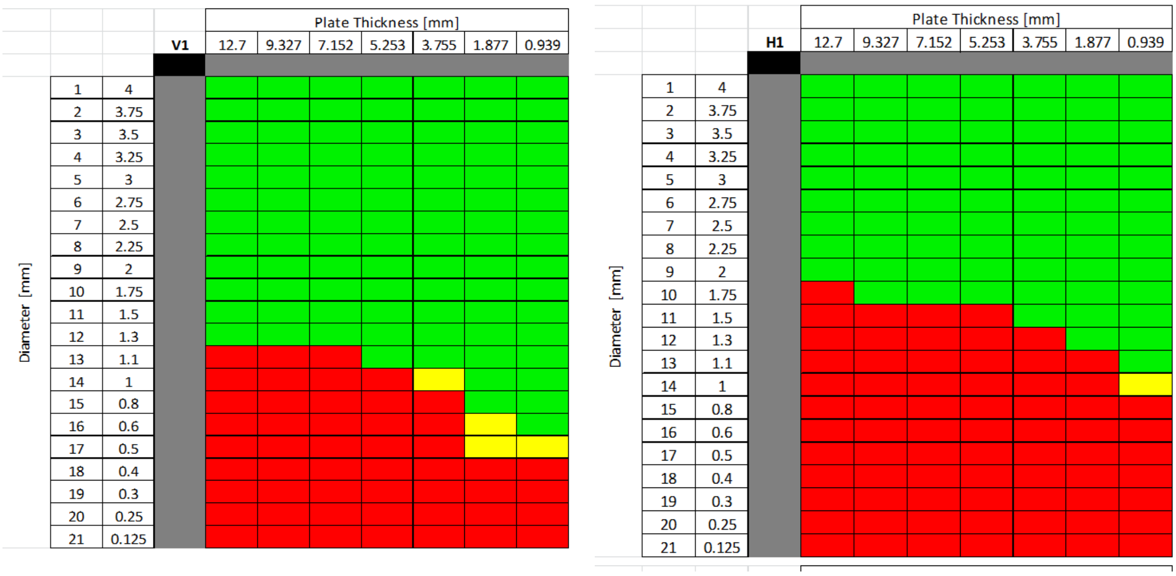

Figure 1. Circular hole resolution versus plate thicknesses for holes with the central axis parallel to the build plane (left) and orthogonal to the build plane (right). See Figure 2 for a description of the color coding. As shown, smaller holes can be resolved when the central axis of the hole is parallel to the build plane because resolution is limited by layer thickness, whereas holes with a central axis orthogonal to the build plane are limited by laser spot size. Spot size is much larger than layer thickness. Also, thicker parts are more prone to oversintering, a phenomenon that causes loose powder to sinter near the surface of a feature because of heat conduction from the sintered part to the surrounding powder, resulting in smaller hole diameters for thicker parts (Seepersad, et al., 2012)

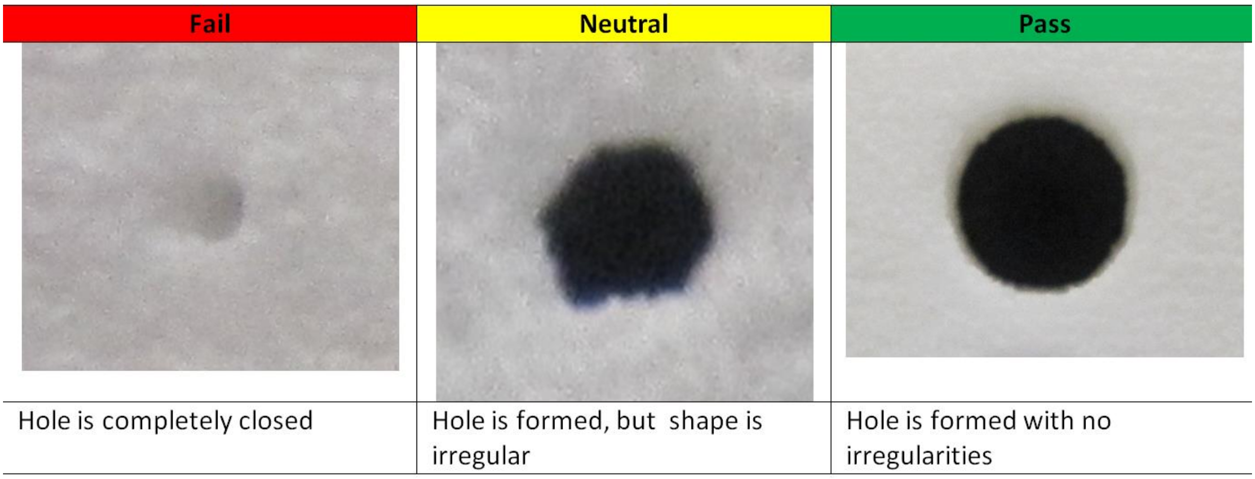

Figure 2. Pass/fail criteria for circular holes (Seepersad et al., 2012)

Metal PBF, particularly direct metal laser sintering (DMLS), places additional restrictions on part features and sizes. Support structures are required in DMLS to anchor parts to the build platform; otherwise, the high residual stresses from melting and solidifying metals in a layer-by-layer fabrication process cause parts to warp and crash the build. Support structures are also required for large horizontal or sharp overhangs and oversized holes to provide the proper thermal environment for laser sintering and prevent part distortion or collapse. Tall, thin features are difficult to build because they are prone to bending by the forces generated as a blade passes over the part to deposit each successive layer of powder.

Other design guidelines focus on orienting parts properly in the build chamber. Large flat planes are difficult to build in an orientation parallel to the polymer PBF build surface because they often warp and curl as each layer successively contracts after sintering, but it is often possible to achieve much flatter surfaces if the flat planes are oriented orthogonal to the build surface. Smoother surfaces in polymer and metal PBF parts are achievable when the surfaces are fabricated either parallel to or orthogonal to the build plane. Angled surfaces are subjected to a stairstepping effect associated with building a sloped surface by stacking subsequent layers in an additive process, as shown in the example guideline in Figure 3. In polymer PBF, where parts can be stacked and nested, parts should be oriented and packed to minimize the total height of the build, thereby minimizing build time and expense.

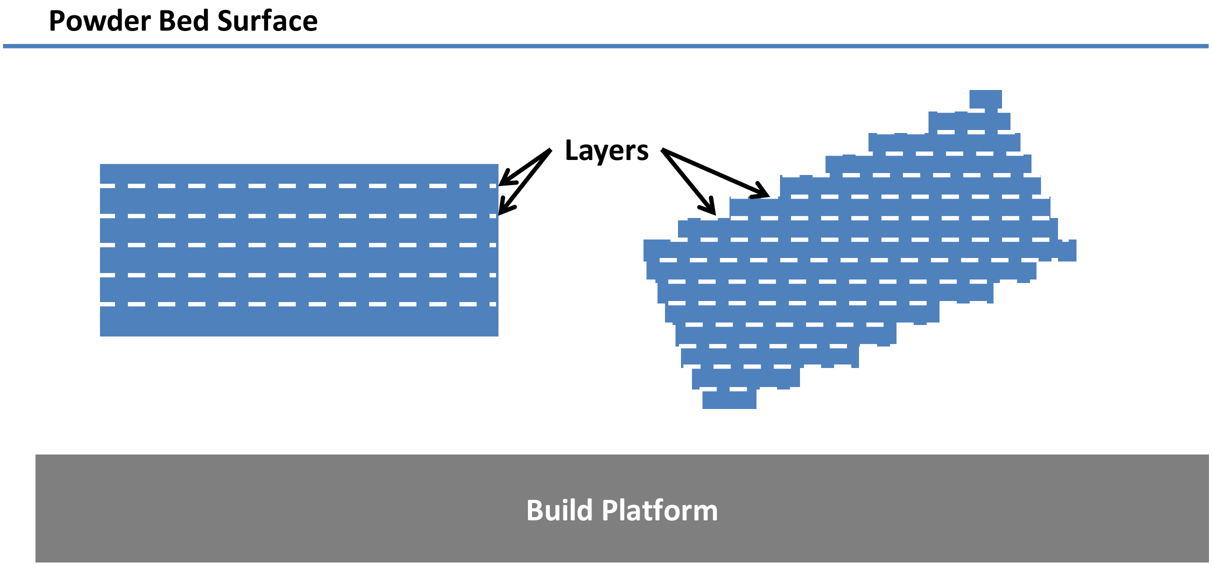

Figure 3. Orient surfaces parallel to or orthogonal to the build plane to avoid stairstepping associated with layer-wise fabrication

In DMLS, parts can be oriented to reduce the need for support structures and to utilize the build space more efficiently. If the central axis of a hole is oriented orthogonally to the build platform, then support structures are not needed inside the hole. If parts are oriented such that the surface area in contact with the build platform is minimized, then more parts can be built in a single build.

Additional guidelines focus on facilitating part post-processing. In polymer and metal PBF, hollow watertight geometries prevent powder removal from the interior of the fabricated part, so access points must be provided for powder removal. In DMLS, internal holes or cavities may require support structures; so, designers must provide access for support structure removal or leave support structures in place permanently.

3 TOWARDS MORE COMPREHENSIVE DESIGN GUIDES FOR AM

The focus of existing guidelines on geometry and dimensions makes them particularly effective for the detailed embodiment stages of design when designers are fine-tuning their designs for production, but they are much less helpful in the preliminary conceptual stages of design and may actually hinder creative ideation for AM. The difficulty is that these types of guidelines tell designers what they can**not** build in AM but give them very little indication of the new types of design opportunities afforded by AM.

3.1 Highlight Design Opportunities Afforded by AM

Focusing on detailed constraints rather than conceptual opportunities is particularly consequential when many designers are designing AM products for the first time. Focusing on detailed constraints may actually contribute to design fixation and poor utilization of AM capabilities. Design fixation is defined as the unintentional adherence to a set of ideas or concepts limiting the output of conceptual design (Jansson and Smith, 1991). Design fixation is typically measured as conformity or similarity to an exemplary solution or specific features of it. Multiple studies have found that both engineering students and practicing engineers fixate on known solutions (Jansson and Smith, 1991; Chrysikou and Weisberg, 2005; Nijstad, et al., 2002; Purcell, et al., 1993; Purcell and Gero, 1996; Smith, et al., 1993; Linsey, et al., 2010), even when they are instructed not to do so, and especially when the solution is familiar to them (Pertulla and Sipila, 2007). When contemporary practitioners design for AM, they are typically solving a problem for which all known solutions are fabricated with conventional subtractive or forming/molding manufacturing processes. In fact, almost all engineered products with which they are familiar--their entire mental library of systems, parts, and features--have been conventionally fabricated. So, it is easy to fixate on conventional solutions and very difficult to conceive of solutions that leverage the extensive design freedoms afforded by AM.

To counter this tendency, design guides need to provide exemplars that uniquely leverage the capabilities of AM and illustrate the new types of designs that are enabled by AM, thereby shifting the designer's context and focus away from the conventional parts on which they may be fixated (Smith and Linsey, 2011). A few preliminary examples are illustrated in Figure 3. AM provides the capability of customizing parts to fit the needs of unique customers. Examples in the top row of Figure 3 include prosthetic limbs that are customized to interface with the unique shape of a particular patient's residual limb and pain-relieving back supports that are custom-fit to the contours of a specific person's back. AM also enables integration of fasteners directly into customized parts. Examples in the second row of Figure 3 include an expanding tower with layers that snap fit into position and a cryptex with interlocking rings that serve as fasteners. AM can also be used to integrate parts for consolidation or multifunctionality. Examples in the third row of Figure 3 include the consolidation of multiple parts and fasteners into a single AM part that provides ventilation ductwork for an aircraft and a helmet insert with a framework of form-fitting plastic surrounding direct write metallic wiring for operating a built-in accelerometer. Finally, AM is particularly appropriate for light weighting components and arranging material in functional patterns. Examples in the bottom row of Figure 3 include lattices that illustrate the gravitational field around the earth and the moon and an aircraft bracket light weighted with topology optimization algorithms that converted a solid structure into an arrangement of lattice elements.

Some design guides are already starting to highlight unique design opportunities afforded by AM. Quickparts (Quickparts (3D Systems), n.d.) provides exemplars of integrating living hinges into parts and integrating multiple parts into a single assembly to reduce assembly time and weight and utilizing lattice structures and surface webbing to lightweight a part without compromising stiffness or strength. Their guide also describes how PBF can be used to fabricate integrated bellows for part flexibility, preassembled rotating axles, compliant buttons and snap clips, and threaded fasteners. Many overview articles describing the design potential of AM also provide examples of the types of unique designs afforded by AM (Hague, 2006; Seepersad, 2014; Gao, et al., 2015). Designers need more and more exemplars to prime them with solutions that are uniquely suited to AM.

3.2 Basic Overview of the Underlying Technology and its Capabilities

Design guides can be more helpful for conceptual design if they not only highlight the unique capabilities afforded by AM but also build an understanding of the underlying technology and its implications for design freedoms and limitations. Many AM design guideline documents resemble long lists of disconnected facts: minimum hole sizes, minimum wall sizes, maximum overhang angles, etc. It is very difficult for designers to remember all of these facts and even when they do remember them, it is difficult to extrapolate those facts to new scenarios that might not be explicitly addressed by the guidelines. In contrast, a basic understanding of the underlying technology can provide a cognitive structure for the various rules and help recall and apply them to new scenarios.

This approach to anchoring various design rules in a basic understanding of the underlying processes is similar to the assumption in cognitive and educational psychology that humans *actively* process incoming information to make sense of it (Baddeley, 1986; Baddeley, 1999). Learners build schemas or knowledge structures to capture the new information and important relationships within it (Johnson-Laird, 1983; Elliott and Chandler, 2008; Bartlett, 1932). As a result, the information will assume a coherent structure that is easier for the learner to recall.

Figure 4. Exemplar parts that illustrate design opportunities with AM. Clockwise from the upper left: A prosthetic customized to fit the residual limb of the amputee (courtesy of Crawford, Neptune, et al., UT Austin); a custom-fit back brace (courtesy of UT Austin); an expandable part that builds in a limited build space and then expands into a tower larger than the build chamber, making use of compliant snap fits to fix the part in its deployed shape (courtesy UT Austin); an aircraft duct illustrating consolidation of multiple parts into one single AM part (courtesy of Boeing); a lattice structure illustrating the gravitational field around the earth and the moon (courtesy of UT Austin); an aircraft engine bracket lightweighted from topology optimization and fabricated with DMLS (courtesy of GE/EADS); a helmet insert with direct write metal wiring integrated into a stereolithography part (courtesy of MacDonald et al., UTEP); a cryptex with interlocking rings that function as fasteners (courtesy of UT Austin)

As an example, in polymer PBF, it is possible to fabricate thinner walls when they are oriented parallel to the build platform versus orthogonal to it. On its own, it is difficult to remember this fact that appears to be somewhat random, but it becomes much easier when it is based on a fundamental understanding of the process. In this case, layer thickness governs resolution of out-of-plane dimensions whereas laser spot size governs resolution of in-plane dimensions. In polymer PBF, typical layer thicknesses are 100 µm; typical laser spot sizes are approximately 500 µm in diameter. Accordingly, it is easier to build thin walls when they are coplanar with the layers.

Similarly, in polymer PBF, small holes tend to be smaller in diameter than their nominal values in the underlying CAD/STL file, but the under sizing is more pronounced for holes embedded in thicker walls and for holes with a central axis orthogonal (versus parallel) to the build plane. The explanation for the impact of orientation is rooted partially in the resolution discussion in the previous paragraph. The explanation for the impact of wall thickness is rooted in the concept of oversintering. Larger surrounding parts require larger amounts of thermal energy for sintering. This thermal energy conducts into the surrounding powder bed, causing sintering of neighbouring powder. When the neighbouring powder is located in a small hole, the phenomenon results in an under sizing of the hole.

In both cases, an understanding of the underlying physics helps the designer place the facts in context and more easily recall them and apply them to different but related features. For example, based on the fundamental knowledge described above, a designer could reason about the likely dimensional imperfections of a 3D lattice structure with thin lattice walls in a particularly low density region of the structure and small holes in a particularly high density region of the structure.

4 CLOSURE

Design guides for AM processes are often focused too exclusively on the limitations of the particular AM process. To support conceptual design effectively, these design guides also need to highlight the new design opportunities afforded by the AM process so that designers can begin building a new mental library of relevant additively manufactured parts and features rather than relying on a restrictive set of conventionally fabricated parts. These design guides also need to build fundamental working knowledge of the process and its role as the genesis for design rules, so that the designer can extrapolate to new features more easily and accurately.

Beyond the basic constituencies of limitations, opportunities, and fundamental process knowledge, it may also be helpful for AM design guides to convey additional information to the designer. For example, many companies are challenged with building a business case for additively manufacturing parts and are finding it quite difficult to do. An AM design guide could start with tips for minimizing the cost of fabricating a part with a specific AM process, but it could also go much further to focus on the entire life cycle cost of the part. AM production can have significant effects on the costs of transportation, inventory, labour, assembly, energy consumption during use (e.g., light weighting), and servicing and repair.

As more comprehensive design guides are developed, it would be interesting to investigate their impact on the design process. By incorporating AM design opportunities into the guides, do they lead designers to conceptualize parts that are especially well-suited for AM--that utilize AM capabilities to fabricate parts with performance advantages over conventionally fabricated parts? Does it matter how the opportunities are presented--as concrete exemplars or abstract features? By incorporating basic knowledge of the underlying fabrication process into the guides, do they lead to designers making fewer mistakes and suffering fewer failed builds versus design guides that include only lists of limitations? All of these questions and many more related topics are opportunities for further research.

REFERENCES

Adam, G. and Zimmer, D. (2014), Design for Additive Manufacturing - Element Transitions and Aggregated Structures. *CIRP Journal of Manufacturing Science and Technology,* Volume 7, pp. 20-28.

Baddeley, A. (1986), *Working Memory.* Oxford, England: Oxford University Press.

Baddeley, A. (1999), *Human Memory.* Boston: Allyn & Bacon.

Bartlett, F. (1932), *Remembering: A Study in Experimental and Social Psychology.* New York: Cambridge University Press.

Chrysikou, E. and Weisberg, R. (2005), Following the Wrong Footsteps: Fixation Effects of Pictorial Examples in a Design Problem-Solving Task. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* 21(5), pp. 1134-1148.

Crucible Design Ltd. (2014), *3D Printing for Manufacture: A Basic Design Guide,* Abingdon, Oxfordshire, UK: http://www.crucibledesign.co.uk/product-design-blog/3d-printing-for-manufacture-a-basic-design-guide.php
Crucible Design Ltd. (2015), *Design Guidelines for Direct Metal Laser Sintering (DMLS),* Abingdon, Oxfordshire, UK: http://www.crucibledesign.co.uk/guides/
Elliott, C. and Chandler, T. (2008), Schemas. In: N. Salkind & K. Rasmussen, eds. *Encyclopedia of Educational Psychology.* s.l.:SAGE Publications, pp. 864-866.
EOS GmbH (2012), *Basic Design Rules for Laser Sintering,* Munich, Germany: http://www.handling.de/upload/06-Basic-design-rules-for-laser-sintering_24906.pdf
EOS GmbH (2015), *Design Rules for DMLS,* Munich, Germany: http://www.3dimpuls.com/sites/default/files/download/dmls_design-rules_en.pdf
EOS GmbH, n.d. *Basic Design Rules for Additive Manufacturing,* Munich, Germany: https://www.eos.info/material-p
Gao, W. et al. (2015), The Status, Challenges, and Future of Additive Manufacturing in Engineering. *Computer-Aided Design,* Volume 69, pp. 65-89.
Hague, R. (2006), Unlocking the Design Potential of Rapid Manufacturing. In: N. Hopkinson, R. Hague & P. Dickens, eds. *Rapid Manufacturing: An Industrial Revolution for the Digital Age.* West Sussex, England: John Wiley & Sons, pp. 5-18.
Jansson, D. and Smith, S. (1991), Design Fixation. *Design Studies,* 12(1), pp. 3-11.
Johnson-Laird, P. (1983), *Mental Models.* Cambridge, UK: Cambridge University Press.
Kranz, J., Herzog, D. and Emmelmann, C. (2015), Design Guidelines for Laser Additive Manufacturing of Lightweight Structures in TiAl6V4. *Journal of Laser Applications,* 27(S1), pp. (S14001) 1-16.
Linsey, J. et al. (2010), A Study of Design Fixation, Its Mitigation, and Perception in Engineering Design Faculty. *Journal of Mechanical Design,* 132(4), p. 041003.
Nijstad, B., Stroebe, W. and Lodewijk, H. (2002), Cognitive Stimulation and Interference in Groups: Exposure Effects in an Idea Generation Task. *Journal of Experimental Social Psychology,* Volume 38, pp. 535-544.
Pertulla, M. and Sipila, P. (2007), The Idea Exposure Paradigm in Design Idea Generation. *Journal of Engineering Design,* 18(1), pp. 93-102.
Purcell, A. and Gero, J. (1996), Design and Other Types of Fixation. *Design Studies,* Volume 17, pp. 363-383.
Purcell, A., Williams, P. and Gero, J.,1(993), Fixation Effects: Do They Exist in Design Problem Solving. *Environment and Planning B. Planning and Design,* Volume 20, pp. 333-345.
Quickparts (3D Systems), n.d. *Rapid Manufacturing: SLS Design Guide - Plastics,* Atlanta, Georgia: http://www.3dsystems.com/company/datafiles/SLS_Guide.pdf?userActiveBreakpoint=1
Samperi, M. (2014), *Development of Design Guidelines for Metal Additive Manufacturing and Process Selection.* State College, PA: MS Thesis, Pennsylvania State University.
Seepersad, C. (2014), Challenges and Opportunities in Design for Additive Manufacturing. *3D Printing and Additive Manufacturing,* 1(1), pp. 10-13.
Seepersad, C. et al. (2012), *A Designer's Guide for Dimensioning and Tolerancing SLS Parts.* Austin, TX, Solid Freeform Fabrication Symposium.
Smith, S. and Linsey, J. (2011), A Three-Pronged Approach for Overcoming Design Fixation. *Journal of Creative Behavior,* 45(2), pp. 83-91.
Smith, S., Ward, T. and Schumacher, J. (1993), Constraining Effects of Examples in a Creative Generation Task. *Memory & Cognition,* 21(6), pp. 837-845.
Stratasys Direct Manufacturing, (2016), *Laser Sintering (LS) Design Guidelines.* [Online] Available at: https://www.stratasysdirect.com/resources/laser-sintering/ [Accessed 12/16/2016].
Yang, L. and Anam, M. (2014), *An Investigation of Standard Test Part Design for Additive Manufacturing.* Austin, TX, Solid Freeform Fabrication Symposium.

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