

Conceptual Design for Additive Manufacturing: Lessons Learned from an Undergraduate Course

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Abstract

Design for additive manufacturing (DfAM) guidelines continue to emerge and evolve as various additive manufacturing (AM) technologies, and the knowledge of their associated end-users/designers, matures. This work summarizes important pedagogical and technical lessons learned from the conceptual re-design of several, diverse parts/assemblies submitted by ~50 undergraduate students cognizant of recent DfAM strategies and guidelines. All students were enrolled in a traditional, semester-long metals AM course designed by the author herein. Students were instructed to select an existing, metallic product and provide a conceptual redesign of that product for subsequent, effective laser-powder bed fusion (L-PBF). Students were instructed that the redesigned concept should have enhanced functionality/specifications and consist of features (e.g. thin walls, bore diameters, etc.) that can be fabricated with minimal risk via current L-PBF systems. The presented results include the types of parts that attract an ‘AM redesign’ effort and the most popular AM-enabled detailed design decisions made. To encourage a more detail-inspired design, DfAM topics were presented ‘backwards’; from post-manufacturing considerations to conceptual design while considering emerging design rules and heuristics. Results indicate that students can become preoccupied with DfAM rules to a point where the design failure modes are not properly accounted for.

KEYWORDS: Design for additive manufacturing, education, training, conceptual design

Introduction

Additive manufacturing (AM), and especially laser-powder bed fusion (L-PBF), has broadened the design space for engineers leading to the production of more material-efficient products for various applications. However, the disruptiveness of AM has led to a disconnect between engineers, both junior and senior, and the effective means for addressing when AM should be employed for a product and the best approach to design for AM (DfAM).

The increased design space offered by AM challenges engineers to think differently. They must consider out-of-norm concepts and shapes that were once infeasible to manufacture. There has been research into how to inspire or guide engineers to take advantage of AM via new designs. For instance, Rosen [1] has provided some methods for engineers to adopt for considering new designs via biomimicry and cellular structures. Booth et al. have provided visual DfAM worksheets to assist students and technicians in identifying AM constraints and important DfAM rules [2].

Engineers involved with design/manufacturing must also remain ‘grounded’, and cognizant of the AM process and its limitations. The process-structure-property-performance relationships inherent to the designed/actual product and its manufacturing method must be considered. There have been studies into the pedagogy of DfAM and its constraints [1–11]. Many of these works have aimed to formalize DfAM, provide DfAM heuristics, determine new training methods for undergraduates and practicing engineers, determine effects of part orientation/geometry on tolerance and surface roughness, and more. The main challenge with DfAM is that the AM technology itself is evolving rapidly. It is possible for some DfAM heuristics to become dated quicker than the publication process inherent to DfAM textbooks and papers.

Background

An undergraduate/graduate course called ‘Additive Manufacturing of Metals’ was taught during the spring semester of 2019 at Auburn University. The course was a survey-type, traditional lecture-style course. Although the course allowed for graduate students to enroll, the majority of students were mechanical engineering undergraduates. Total enrollment was 48 students (including 3 graduate students).

No textbook was adopted for the course. Instead, students were exposed to the methods and findings from various academic papers Refs. [1–11], online videos, guest speakers, and the experience of the author. A particularly useful paper by Pradel et al. was employed for discovering and teaching DfAM papers based on their detailed literature survey [3].

The first half of the semester was devoted to the major AM types, case studies and terminology. Throughout the semester, students were provided with “In the News” updates before lecture that summarized key advancements in the field and industrial use of AM. The second half of the semester focused on DfAM – including detail, embodiment and conceptual design heuristics and methods as they pertain to AM – especially metals AM. Some other topics discussed with DfAM included: a Review on basic design and optimization principles/methods; Post-manufacturing techniques (wire EDM, heat treatment, surface finishing, etc.); AM process chain, digital thread for AM; Computer-aided design considerations for AM; and material selection/substitution. Students were taught DfAM by using a ‘backwards’ approach used by Pradel et al. Meaning, students were first introduced to concepts & rules/heuristics related to post-AM operations, followed by (in order): part programming, detail design, embodiment design, conceptual design, and requirements. By teaching detailed design first, students were being steered more toward embodiment design approaches which depend more on material, details, assembly and functionality [12]. This presentation method is believed to make students more likely to consider post-AM and programming/CAD issues during initial design – as these final two steps can influence DfAM more so than other design-to-manufacturing efforts.

For the final month of the course, students were assigned a project that challenged them to take any product and re-design it for AM as to enhance the product. All students were instructed to consider several rules for DfAM and to re-design while being cognizant of these rules. They were to identify features that hinder the additive manufacturability of the legacy part they considered. Students were also tasked in determining possible failure modes of the AMed part. Sketches of the new AM product were asked to be provided. Students had the option to work with a partner on the design project. The major DfAM rules students considered included: smallest feature, functional design, surface quality, dimensional accuracy (as-printed), material availability,

time, powder entrapment and de-powdering, size constraints, mechanical performance, part orientation in AM chamber, support structures, and more.

Results

Several solutions were submitted as part of the course project, however, only a select few are presented to demonstrate the conceptual DfAM approach employed by undergraduate students. It is also the goal to demonstrate how students addressed the limitations/opportunities of metals AM. It is worth noting that some of the designs not provided here include a vegetable peeler, carburetor main body, metal baseball bat, golf club, hammer head, axle shafts, piping elbows, iron soleplate, and a dock cleat. The effort dedicated by the students on the project assignment varied. Students were generally graded on whether instructions were followed and for completeness.

Cattle brand

A group of two students identified a cattle brand as a candidate for re-design for AM. The design pitch indicated that there is an opportunity to make unique/custom brands with features less harmful to livestock. As shown in Fig. 1, the students called out regions along a traditional cattle brand that require careful attention for DfAM.

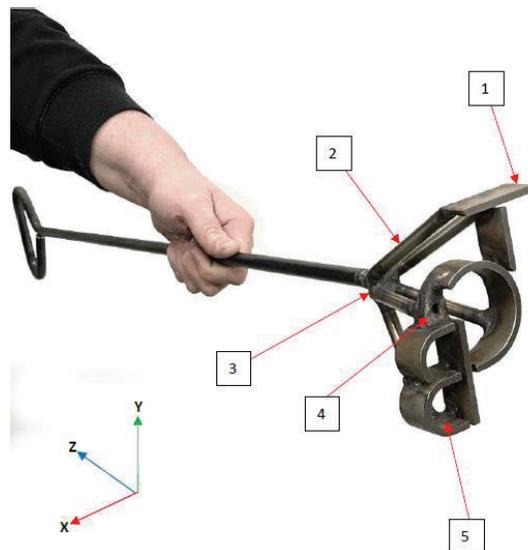


Fig. 1 Legacy cattle brand design with regions challenging the effective AM labeled.

Label descriptions for Fig. 1:

1. Lack of fillets in design lead to stress concentrations and resolution difficulties.
2. Even though the main loading will occur parallel to the build (Z+) direction, any accidental loading in the XY plane, perpendicular to build direction, will produce excessive transverse shear in these thin beams.
3. With a Z+ build direction, most of this brand will require excessive amounts of support material. Which will be impossible to access/remove during the post processing steps.
4. Voids in the design will behave as sites for fatigue crack nucleation and propagation.
5. Overhangs in the part will require support.

- In general this brand is very tall for AM processing, this is a major limiting factor to its additive manufacturability because there is a strong positive correlation between cost and Z axis height.

Based on the ‘problem areas’ shown in Fig. 1, a new cattle brand design, with enhanced features, was proposed for AM as provided in Fig. 2. Note that the letters on the AM cattle brand were arbitrarily chosen, but represent a sequence of letters/numbers that may be used for branding.

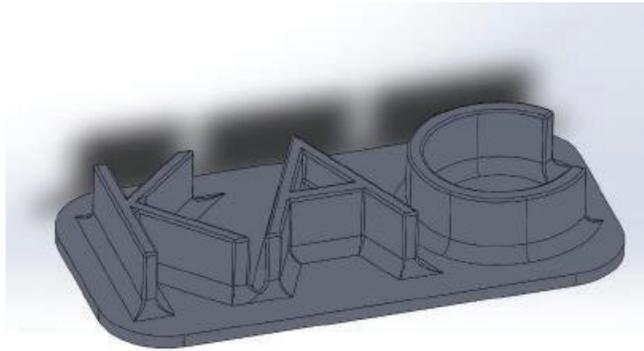


Fig. 2 Proposed cattle brand design for AM.

Zipper

One student challenged the traditional zipper design – especially with respect to its extended tab feature which can be difficult to manage for some people. Of course, such a device would be infeasible to fabricate with AM economically, yet the provided solution elucidates more on the DfAM approach. Sketches of the re-imagined zipper for AM are provided in Fig. 3.

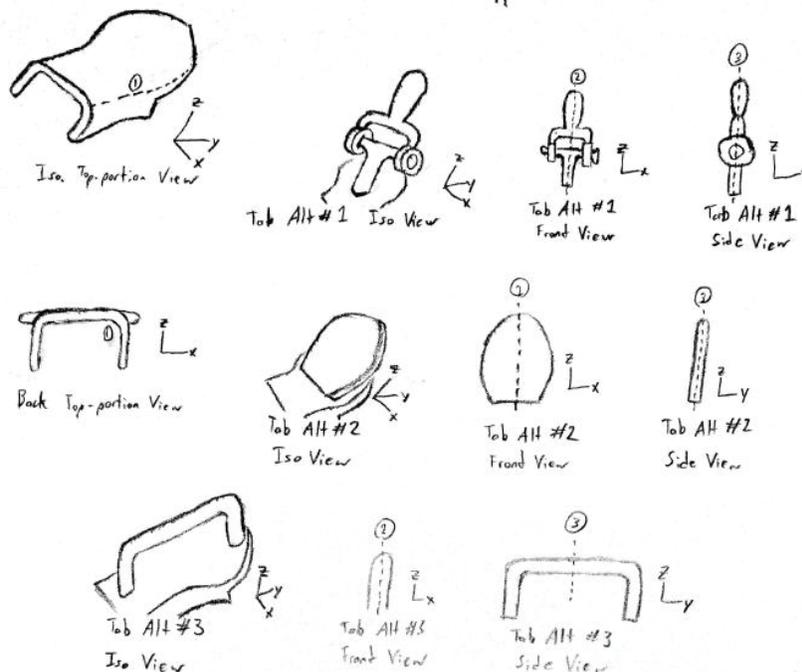


Fig. 3. Conceptual design sketches for re-design of a zipper for metals AM.

The student indicated that the primary reason for re-designing the zipper was usability. A noted challenge would be redesigning zippers to not have any hard 90° transitions between faces. In addition, the printing a single part that has interlocking pieces is a challenge. As discussed by the student the first alternate design (in Fig. 3) can be arranged in such a way, that if oriented with y-dimension perpendicular to the building plane (so that x and z are within the 2D build plane), the tab can be supported free of the zipper, allowing for easy support removal. The student mentioned that the AM zippers were all designed to have their y-dimension perpendicular to the build plane for the ease of support removal. The student was aware of surface roughness effects and discussed how the orientation of the zippers on the substrate could help control this feature.

LEGO® dies

LEGO dies and other polymeric dies are not currently produced via AM because of the low tolerance and demand for a pristine surface. As shown in Fig. 4, the student addressed some major challenges in using metal AM for fabricating LEGO dies. The student was clearly aware of application environment and how this would impact the material selection and design. As mentioned by the student, thermal cycle fatigue resistance is an important property of the LEGO die as it would experience ~200 °C thermal cycle for each use. To survive this use a metal with high thermal conductivity will be more beneficial so that the heat can be transferred evenly through the part and into the surroundings. The student mentions stainless steel as meeting this criterion better than other common AM metals. The surface roughness, minimum feature size and corner radii of the die were mentioned as major challenges for ensuring a successful AM LEGO die.

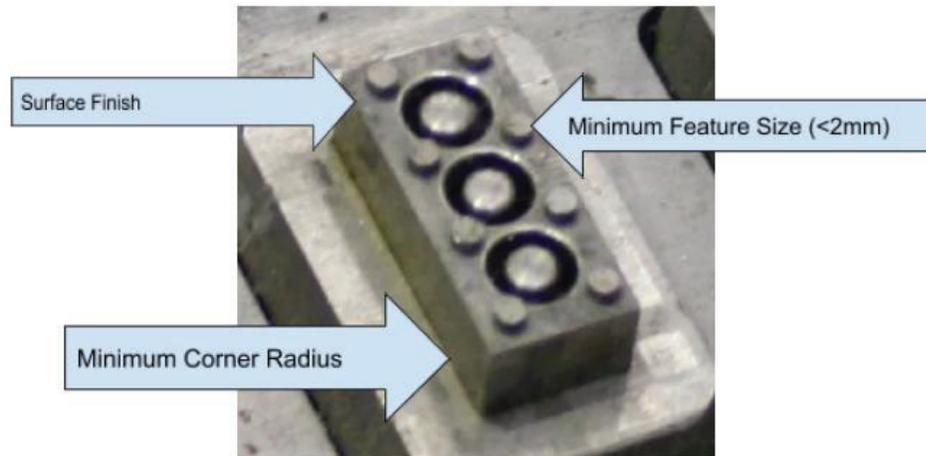


Fig. 4. A photo of a LEGO die with challenges for AM pointed out.

Bicycle stem

A team of two students worked on the re-design of a typical bicycle stem for AM. A bicycle stem is a bracket that connects the handlebars to the headset on the frame. A common bicycle stem with noted challenge areas for DfAM are provided in Fig. 5. Solutions to the problem areas marked in Fig. 5, as provided by the students, is also provided below Fig. 5. This group was effective in considering the actual build plan for the AM of the bicycle stem, and the envisioned orientation/placement of the part on a L-PBF build plate is provided in Fig. 6.

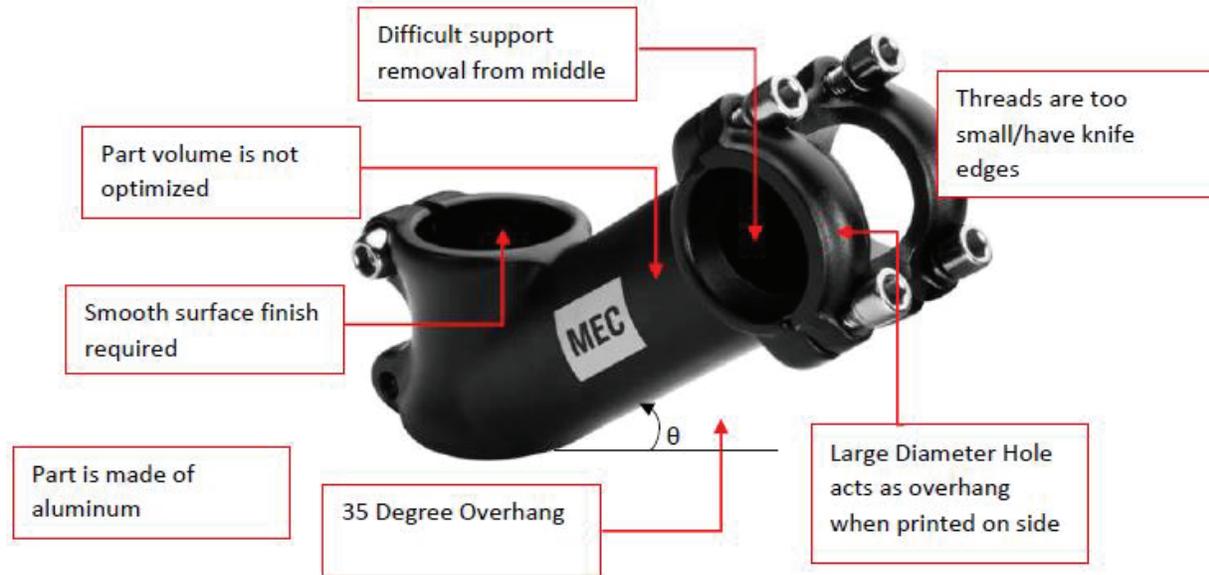


Fig. 5. A photo of a bicycle stem with challenges for AM pointed out.

Some notes from the students with regard to the challenges in fabricating the bicycle stem via AM are provided below.

1. This part will need to be printed on the side to avoid having the large 35-degree overhang. This will also act to support the load along the print plane to prevent delamination.
2. The frame-side hole will require support between the diameter.
3. The part will use compatible metals such as titanium and steel. It is necessary to reconsider if the material can withstand the environment, weight, and strength.
4. Because threaded holes are not manufacturable via AM, post-AM tapping will be required to create the threads.
5. To fix both the optimization issues and the support removal issue, a topology optimization method and FEA method could be employed to use less material in the shaft. This would reduce the weight of the part and allow holes for support to be removed easier.
6. The inside of the holes will need post-AM machining or sanding so that the handlebars and headset don't get scratched

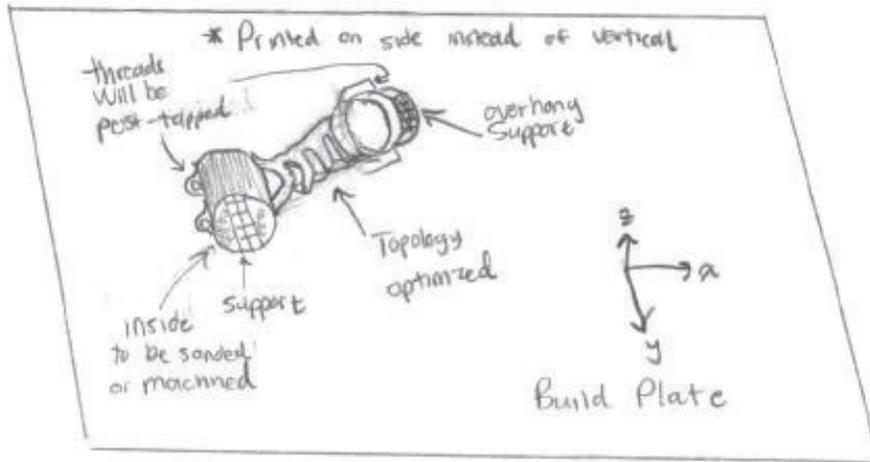


Fig. 6. A sketch of how the bicycle stem would be positioned within a L-PBF chamber for fabrication. Some notes are provided by students in the sketch.

Fish hook

One student provided a conceptual design for a new fish hook that employs more curvature and a j-type top portion to allow for one to wrap a fishing line around the hook rather than using a hole. This concept is shown in Fig. 7. The provided a simple new functionality of a fish hook based on considering the advantages of AM, yet was still considerate of the limitations as provided by the use of support structure.

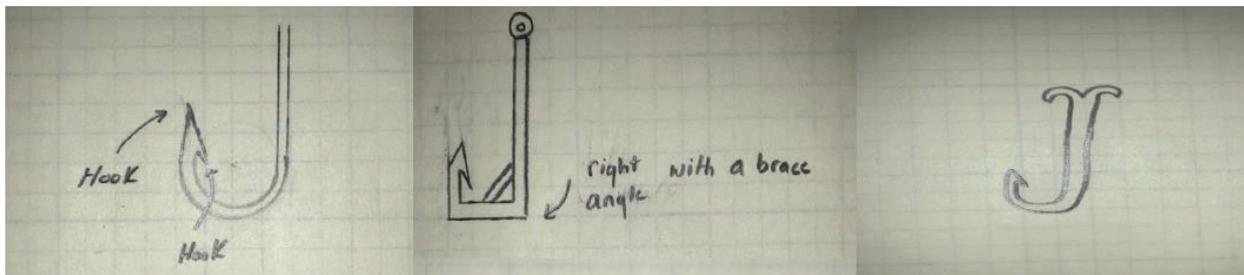


Fig. 7. Student sketches demonstrating (left) a typical fish hook, (middle) an AM fish hook with support brace concept, (right) a hole-less fish hook concept for AM.

Aerospace rotor

One student investigated the challenges in adopting AM for the fabrication of an aerospace rotor (Turbocam). This specific rotor is one of the first components inside a gas turbine, specifically the compressor. The student noted how the rotor is a critical component to gas engine operation and public safety and that common failure modes are erosion and fatigue failure due to high cyclic loading operations. As shown in Fig. 8, some common AM design rules are addressed at pointed-out locations on the rotor. The student was aware of the build envelope constraint for the selected rotor; however, the student noted alternate AM methods (to L-PBF) such as Big Area AM (BAAM). A re-design of the rotor for AM, as provided by the student, is shown in Fig. 9.

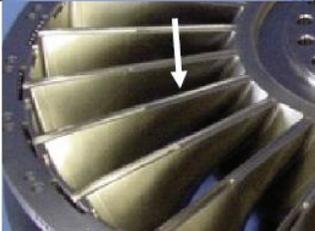
Rules Violated	Explanation	Annotated Picture
Maximum Part Size	This rotor features an outside diameter of 23 inches. Most metal additive manufacturing machines do not allow for this big of a build volume.	
Minimum Wall thickness	This rotor features a total of 26 blades each of very small thickness.	
Minimum Feature size	This rotor features very small channels for the blades. These channels are used to increase the outlet pressure from the rotor.	
Knife Edges	At the bottom side of each blade there are sharp edges.	
Faces Requiring Support	At the end of the part there are retaining features that have overhanging features.	

Fig. 8. AM challenges associated with an aerospace rotor.

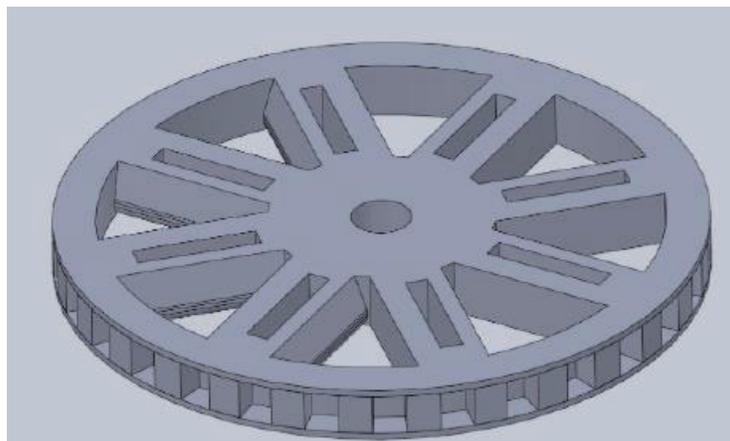


Fig. 9. Proposed re-design of an aerospace rotor for AM.

All drawings and reports were compared against each other in order to determine general DfAM approaches adopted by the students. It was clear that students set higher priority to ensuring their re-designed parts were additively-manufacturable. Re-designed parts did not necessarily have better features for enhancing product lifetime (failure resistance). This could be attributed to the assignment time constraint hindering any ability for students to predict and compare part performance during application. Students re-designed parts for functional improvement while not altering design concepts drastically. By teaching detail-driven DfAM, students appear to have focused more on embodiment of their legacy products rather than radical new concepts. In their focus toward embodiment and functionality, the vast majority of selected parts for re-design were not assemblies in need of consolidation, rather, they were single-bodied parts. Students were clearly able to use common DfAM rules and to identify potential geometric alterations in legacy parts for improving additive manufacturability.

Conclusions & Remarks

By inspecting the sketches and write-up of senior-level mechanical engineering undergraduate students that focused on the conceptual, embodiment and detailed designs for the AM of legacy, everyday parts, it was possible to take a ‘snap shot’ of how students utilize DfAM heuristics and rules. All students were presented with several DfAM concepts/approaches over half a semester. The below are some major conclusions and remarks from this study.

1. Teaching the DfAM stages backwards encourages students to focus more on embodiment rather than concepts. This could be beneficial for design efforts focused more on product enhancement.
2. Although part consolidation is an advantage provided through AM, the vast majority of students did not select legacy products with multiple joints/parts.
3. Students can easily apply DfAM rules for aiding the re-design of parts after they are provided with lists and worksheets from the open literature. Students can become preoccupied with these rules and provide less attention to designing against product failure during application.
4. The assignment, although limited in scope and time, provides a valuable opportunity for students to rehearse important DfAM rules and to critically evaluate the functionality of current products.

It is recommended that DfAM rules involve multiple levels of specificity – with their being broad, agnostic sets of rules that can apply to a particular AM method, and then more detailed rules for specific AM systems and materials. More agnostic DfAM rules are highly needed to combat their antiquation as AM technology continues to rapidly evolve. The use of ‘cheat sheets’/worksheets and lists with visual graphics should aid the DfAM rule retention and usability moving forward.

Acknowledgements

A portion of this work was conducted while the author was a faculty member at Auburn University. All students were made aware that their submitted work could be included in a research article, and only the sketches/photos generated by consenting students have been included in this paper.

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