Design for the Additive Manufacturing Process Chain

David W. Rosen
The G. W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332
e-mail: david.rosen@me.gatech.edu

Digital Manufacturing and Design Centre
Singapore University of Technology and Design
Singapore, 487372

Abstract

Post-processing operations are required for most additive manufacturing (AM) processes. For production parts, consideration of these post-processing operations during design is critical to achieve design requirements. For both metal and polymer parts, the sequence of steps in the process chain can be extensive. A design framework called the Process Chain Map (PCM) is introduced in this paper that explicitly relates design requirements for the part to each step in the AM process chain. This PCM visually shows the role of each step in the process chain and facilitates communication among design and manufacturing personnel. Software implementation of the PCM enables generation of system-level problem formulations of multidisciplinary design optimization problems. An example of a metal AM part demonstrates the PCM and the formulation of such a design problem.

Keywords: design for additive manufacturing, manufacturing process chain, process chain map

Introduction

Post-processing operations are required for most additive manufacturing (AM) processes. Consideration of the entire process chain, from the AM process to all the post-processing operations, during design is critical to achieve design requirements. For metal parts, heat treatment, support structure removal, and finish machining are frequently required to convert the AM-fabricated part to its final state. Also, polymer parts usually require some post-processing operations, including support removal and finishing [1]. A technique called the Process Chain Map (PCM) is introduced in this paper that explicitly relates design requirements for the part to each step in the AM process chain. This PCM visually shows the role of each step in the process chain and facilitates communication among design and manufacturing personnel.

A framework for part design across the process chain is presented based on the PCM. The objective of the framework is to ensure that part designs are optimized for performance and for the capabilities and limitations of the manufacturing processes. Accordingly, each step in the process chain should be optimized for the system-level objectives, in addition to part performance optimization. Leveraging multidisciplinary design optimization methodology, the framework includes design optimization problem formulation where the system level design problem is decomposed into a series of subsystem problems that correspond to the steps in the process chain. Requirements embodied in the PCM are incorporated into the design problem formulation. Influences of manufacturing processes on each other throughout the process chain are modeled using coupling variables among the corresponding subsystems.

An example of a metal AM part demonstrates the PCM and the formulation of a design for the process chain problem. The specific part is a bike stem to be fabricated in metal powder bed fusion (PBF). Results show that the PCM successfully models relationships between design requirements and the steps in the process chain and guides the designer in developing part designs for the process chain.

Process Chain Map

The process chain map (PCM) is intended to be a visual representation of the relationships between steps in the process chain and how those steps contribute to satisfying design requirements. An example PCM for metal PBF is shown in Figure 1. Across the top is the sequence of manufacturing processes in the process chain. The first column contains the design requirements for the part in terms of shape, tolerance and surface finish requirements, and mechanical properties. The user of the PCM needs to decide the level of detail of the requirements. For a specific part design, it may be important to include different tolerances if they are achieved by different manufacturing processes. In this example, different mechanical properties are included for bulk regions of the part, as well as surface properties, but this may not be relevant to all parts. In the body of the PCM, entries (green checks) indicate which processes contribute to achieving the requirement.

In this illustration, the process-requirements relationships are shown qualitatively. An alternative usage of the PCM is to include quantitative values in the table to indicate the extent to which the requirement is achieved or the specific values of, for example, mechanical properties achieved by the process. This is similar to the development of Quality Function Deployment charts [2] that capture qualitative relationships between customer requirements and engineering characteristics. More complete implementations of QFD added quantitative entries so that the importances of engineering characteristics could be rank-ordered.

Design Requirements	AM Process	Stress Relieve	Bead Blast	Cut Supports	Annealing	Machining	Can Achieve?
Part shape	✓	✓				✓	✓
Tolerances						✓	✓
Surface finish			✓	✓		✓	✓
Mechanical properties							
surface			✓		✓	✓	✓
bulk					✓		✓

Figure 1: Process chain map for metal powder bed fusion.

The PCM can serve multiple purposes. First, it documents the process chain for the part so that all participants in product development can understand the sequence of processes. The PCM aids communication among the product development team; if someone does not understand the need for a process, they can discuss with the relevant manufacturing personnel. Also, the PCM clarifies the role of each process in the process chain, indicating to which requirement(s) it contributes.

Further, software implementations of the PCM can be used for various design, manufacturing, and management purposes.

- Lay out the entire process chain
- Relate design requirements to specific processes in the process chain
- Visual depiction aids understanding of each process's role
- Communication aid

Additive Manufacturing Process Chains

As illustrated in Fig. 1, AM process chains can be extensive. Final part characteristics can be rather different than those produced by the AM process and it is imperative that designers design with final part properties and characteristics.

In metal PBF, parts are fabricated with support structures, also called anchors, that fix the part to the build platform and prevent the part from warping due to residual stresses. Support structures also conduct heat from the laser to the build platform to reduce the likelihood of hot spots. These supports need to be removed by a machining operation: cutting, EDM, machining, etc. However, if supports are removed while the part has significant residual stresses, it can deform considerably. To prevent this, a stress relief heat treatment is typically performed while the part is still attached to the build platform. The stress relief not only relaxes residual stresses, but can also modify and homogenize metal microstructures and significantly reduce mechanical property anisotropies. Additionally, annealing, solution annealing, and aging heat treatments may also be performed to modify microstructures and properties, in addition to (or instead of) stress relief.

After PBF, parts are buried in the powder bed. It is necessary to remove the loose powder. Sometimes, people use brushes to remove powder particles from part surfaces, crevices, or holes. Automated depowdering stations are also available to automatically rotate build platform with parts to facilitate powder removal from different directions and from internal channels. Part surfaces tend to be fairly rough after metal PBF so various surface finishing operations may be performed on parts before or after removal from the build platform. Blasting with beads, sand, and ice is common. Finish machining is also common for part surfaces that have high accuracy, shape, or surface finish requirements.

Most of this discussion applies to metal directed energy deposition (DED) processes as well, except that parts are not buried in a powder bed. Parts are typically built on a build platform; parts either need to be removed from the platform, or the platform is incorporated into the part design, but often needs to be cut to shape. Heat treatments and finish machining are common.

For polymer processes, the process chain is also important. Support structures are used in most polymer processes, with the exception of PBF. Surface treatments (bead blasting, sanding) are commonly used to provide desired surface finish. Some machining or hand work may be performed to ensure correct shapes and accuracy requirements are met.

In summary, parts are rarely ready for use after only the AM process. One or more post-processing steps is used frequently to ensure parts satisfy requirements. Some of this post-processing can significantly impact part characteristics and properties so it is important to capture their effects.

Design for the Process Chain Method

A framework has been developed for the design of parts for the process chain, based on methods from Multidisciplinary Design Optimization (MDO) [3,4]. The objective is to design part shapes and find dimension values that satisfy as well as possible design requirements and constraints. Many times these requirements and constraints will not be satisfied by the AM process, which is why subsequent post-processing steps are needed.

The proposed approach starts with the formulation of the overall design problem, that is referred to as the part-process chain co-design problem. An example problem formulation is shown in Fig. 2 (based on [5]). At the top, the overall problem formulation is given as finding part shapes and dimensions, part characteristics, and process settings for all of the manufacturing processes in the process chain. This MDO problem seeks to minimize a measure of deviation from goals on, for example, performance requirements (e.g., maximum stress, maximum deflection), economic objectives (build time, cost), and weight. Design variables, constraints, and objectives are often related to the requirements listed in the process chain map.

The overall problem is decomposed into various subsystems that represent each step of the process chain from the process chain map, as well as part performance design. The problem formulation is illustrated with subsystem design optimization problems, but the overall design method need not distribute optimization in this manner, which will be discussed later. An advantage of this approach is that typically different analyses are performed for the different subsystems and these analyses can be performed independently from one another. The disadvantage is that the various subsystem design problems cannot be solved independently. This is easy to see if we consider mechanical properties. Elastic modulus and yield strength, among other properties, are needed for structural performance analysis of the part being designed. If fatigue is important, then surface roughness is important to consider. Since these properties and characteristics are the results of the entire process chain, the subsystem design problems are coupled, which has important implications. First, the problem coupling implies that some quantities are coupled, which may include design variables or other intermediate variables. Mechanical properties, such as elastic modulus, are good examples of coupled quantities. Second, the problem structures usually determine the sequence that subsystem problems should be solved. With few exceptions, the subsystem solution sequence should be the same as the process chain, with part design being the last subsystem to be solved.

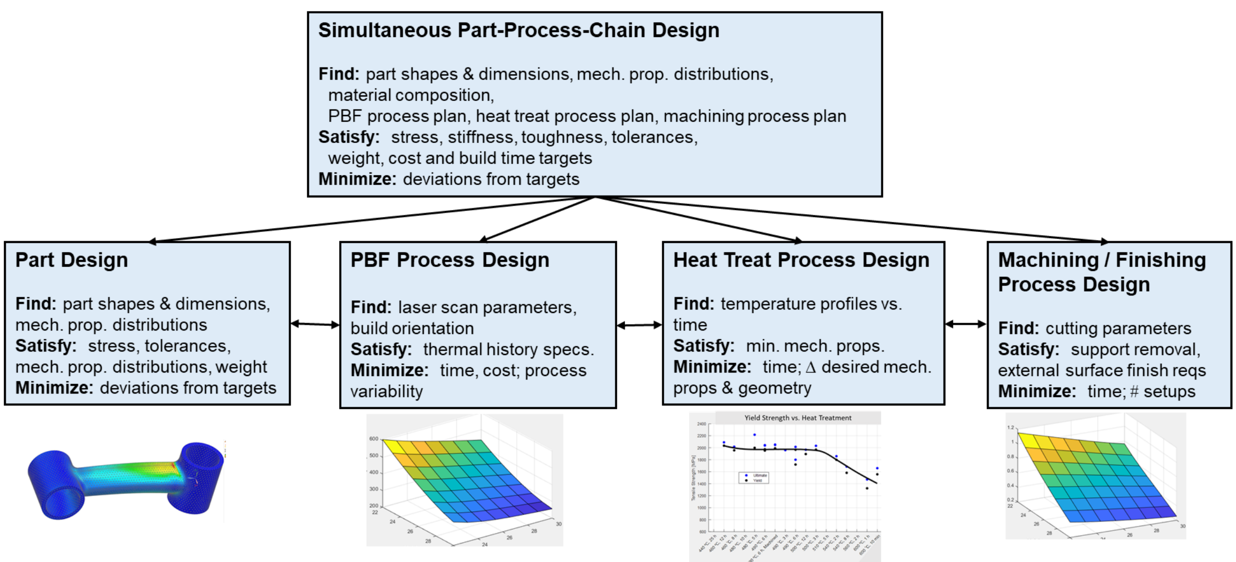


Figure 2: Product-process chain co-design problem formulation.

To deal with subsystem coupling and identify suitable work flows, we use an extended design structure matrix diagram [6], as shown in Fig. 3. In the middle part of the figure, the four boxes denote the four subsystems from Fig. 2, but note that part design corresponds to the box labelled 'D4 – Design.' D1-D3 are the three manufacturing processes in the process chain. Information flows are indicated by the green solid arrows that connect the boxes. Output variables from D1 flow to D2, D3, and D4. Similarly, output variables from D2 flow to D3 and D4, etc. Additionally, outputs from D2-D4 can flow back up to D1 and potentially the other boxes (the diagram is shown fully connected, but need not be so). Solid black arrows pointing downwards from the D1-D4 boxes indicate optimization objectives, J1 to J4 respectively, that are computed by the subsystems. These objective quantities are inputs to the system-level performance evaluation where they are used to compute overall optimization objective function J*. Execution proceeds sequentially from D1 to D4 then to the system level performance evaluation. After evaluation, the system level optimization tests for convergence; if not converged, iterations continue starting again at D1.

With this presentation, it should be clear that the process chain map can be used to directly develop part design optimization problems for the process chain that can be solved using MDO methods.

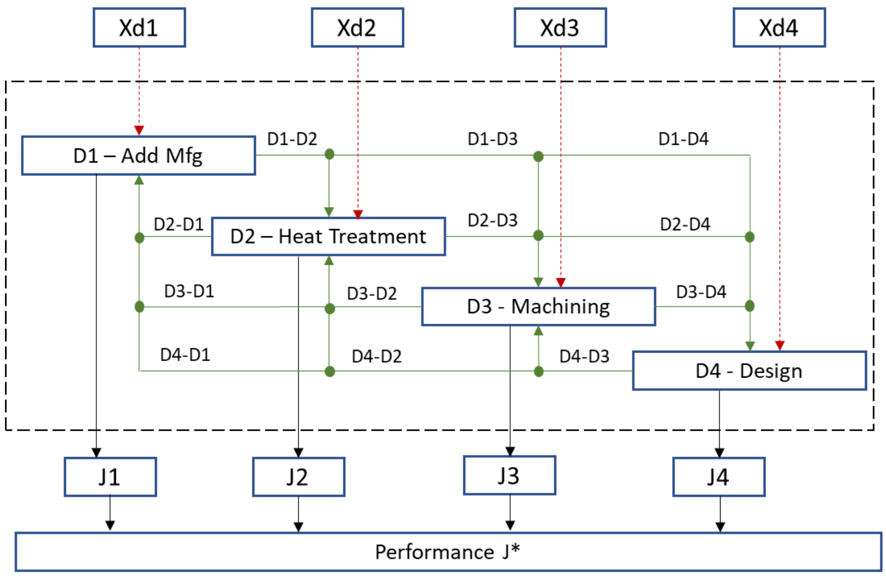


Figure 3: Information and execution flows in the MDO problem expressed using an extended design structure matrix diagram.

Example

A bike stem part will be used to illustrate the application of the process chain map and concepts around design for the process chain. A bike stem attaches the handlebars to the steering fork as illustrated in Fig. 4. We assume that bike stems are loaded in bending, torsion, and in tension. The titanium alloy Ti-6Al-4V is selected for the material and we will plan for production (high volume) manufacturing using PBF.

Requirements for the bike stem include supporting those expected loads, light weight, cylindricity tolerances on the cylindrical bores (large holes that mate with the steering shaft and the handlebars), a perpendicularity tolerance on the two bores, and surface finish requirements overall (< 40μm Ra), in the bores (<μm Ra), and on the sides of the bores (< 1μm Ra).

Figure 4: Bike stem part.

Topology optimization will be used to reduce part weight. The AM process chain consists of the PBF process followed by a stress relief heat treatment and an aging heat treatment to ensure maximum mechanical properties are achieved. Support structures will be removed using EDM. Parts will be bead blasted to ensure that surface finishes overall are below 40μm Ra. Finally, finish machining will be performed on the bores and side surfaces to ensure that tolerances and surface finish requirements are met.

Design Requirements	AM Process	Stress Relieve	Age (8 hrs)	EDM Supports	Bead Blast	Machining	Can Achieve?
Part shape							
Lattice stem	✓	✓					✓
Bores (2)	✓					✓	✓
Slits in bores						✓	✓
Bosses	✓	✓				✓	✓
Tolerances							
Cylindricity-2X						✓	✓
Perpendicularity						✓	✓
Surface finish				✓			
Inner cylinder						✓	✓
Bore sides						✓	✓
Overall					✓		✓
Mechanical properties							
surface			✓		✓	✓	✓
bulk			✓				✓

Figure 5: Process chain map for the bike stem part.

As can be seen in the right-most column of Fig. 5, all requirements can be achieved using this process chain map. Since the engineering work has not yet been completed, however, this conclusion should be considered as preliminary and an indication of what should be possible. The role of each step in the process chain can be understood by identifying requirements to which each contributes. For example, the interpretation of the stress relieve process is that it relieves residual stresses which enables the overall stem to maintain its desired shape and ensures the bosses (for the bolts and nuts used for attachment) have correct shapes and positions. Aging contributes to mechanical properties but does not have much impact on part or feature shape. Bead blasting affects overall surface finish and contributes to surface mechanical properties (surface treatments typically induce compressive stresses). Machining fine-tunes feature shapes and enables achievement of tolerances and surface finish requirements.

Results to date are as follows. Topology optimization results are shown in Figure 6a. After further design, the final part is shown in Fig. 6b. To maximize the number of parts that fit on a build platform, the stems were oriented vertically; lattice structure struts were adjusted so that they could be fabricated without requiring support structures. Bosses were added for the bolts and nuts required to fasten the stem. After finalizing the part design, the PBF build layout and support structures were designed. A view of the stem oriented vertically is included in Fig. 7a. Some support structures are needed in the cylindrical bores. It was decided to use a teardrop shape for these bores, effectively adding gusset supports in the bores, instead of conventional vertical support structures since gussets should lead to faster machining times. Orthogonal views of the stem are shown in Fig. 7b. The bosses on the sides of the top bore require support structures, as can be seen in Fig. 7c, which shows an array of 20 bike stems on a single EOS M290 build platform. Solid supports were used at the bottom of the stem to facilitate heat conduction into the build plate, as can be seen in Fig. 7d.

topology optimized design b) final design

Figure 6: Bike stem designs.

Process planning of machining operations was performed to remove support structures, machine the bores, and slit the bores to permit assembly. Simulations of these operations were also conducted, the results of which are shown in Figure 8.

The design for the process chain framework has not been fully implemented yet, so results from the application to this example are not yet available.

Conclusion

Post-processing operations are required for most additive manufacturing (AM) processes. As a consequence, consideration of these post-processing operations during design is critical to achieve design requirements, hence the need for design for the AM process chain methods. The Process Chain Map (PCM) was introduced in this paper as a technique to explicitly relate design requirements for the part to each step in the AM process chain. This PCM visually shows the role of each step in the process chain and facilitates communication among design and manufacturing personnel. A framework for design for the process chain was introduced based on methods from MDO. An example of a metal bike stem part demonstrates the PCM and the formulation of such a design problem. In conclusion, the PCM appears to be a useful technique for documenting and communicating manufacturing process chains. Further, the PCM can assist in formulating design for the process chain multiobjective optimization problems.

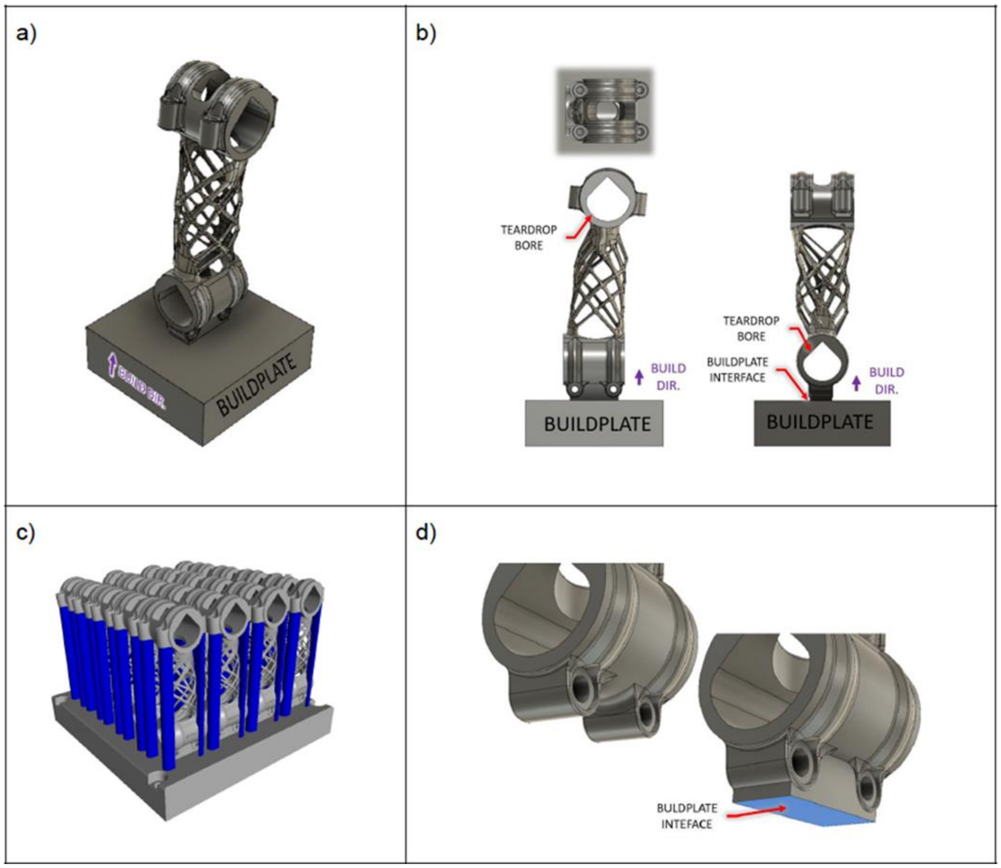


Figure 7: Bike stem PBF manufacturing: a) single stem positioned on build plate, b) two views of bike stem showing teardrop hole shape in bores, c) array of bike stems on build platform, d) support structures at base of part.

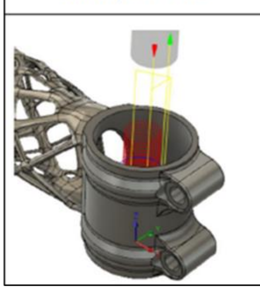
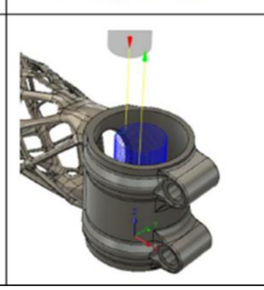
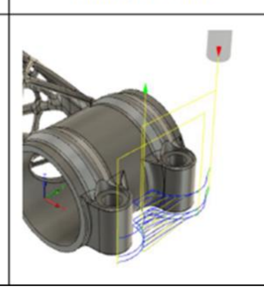
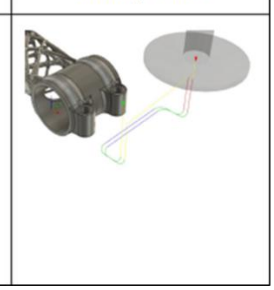
Op 1. Rough milling of bore (adaptive clearing) *Remove tear drop geometry and overprint efficiently*	Op 2. Finish boring *Create a precise bore with high surface finish*	Op 3. Removal of buildplate interface (adaptive clearing) *Remove non-functional material that made up interface efficiently*	Op 4. Slitting *Slit the bore so that it may properly clamp when tightened on the fork steerer tube/handlebars*
5min, 34 sec	6 min, 23 sec	1 min, 15 sec	6 min, 8 sec
			

Figure 8: Machining process planning with estimates of machining times.

Acknowledgements

Partial support from the Advanced Manufacturing and Engineering, Industry Alignment Fund program in the Singapore National Research Foundation, grant A19E10097, is gratefully acknowledged. Thanks to students Jaime Berez and Elliott Jost in my ME7227, Rapid Prototyping in Engineering, course for their efforts developing the bike stem example.

References

1. Gibson, I, Rosen, D.W., Stucker, B., Khorasani, M., *Additive Manufacturing Technologies*, Third Edition, Springer, 2021.
2. Hauser JR, Clausing D., "The House of Quality," *Harvard Business Review*, May, pp. 63-73, 1988.
3. Sobieszczanski-Sobieski J, Agte JS, Sandusky RR (2000) "Bi-level integrated system synthesis." *AIAA J*, 38(1):164–172.
4. Tosserams S, Hoftkamp AT, Etman LFP, Rooda JE (2010) "A specification language for problem partitioning in decomposition based design optimization." *Struct Multidisc Optim*, 42:707–723.
5. Sambu, S., Chen, Y., and Rosen, D.W., "Geometric Tailoring: A Design For Manufacturing Method for Rapid Prototyping and Rapid Tooling," *ASME Journal of Mechanical Design*, Vol. 126, No. 4, pp. 571-580, 2004.
6. Lambe, A.B., Martins, J.R.R.A. "Extensions to the design structure matrix for the description of multidisciplinary design, analysis, and optimization processes." *Struct Multidisc Optim*, 46, 273–284, 2012.