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Generalized requirements and decompositions for the design of test parts for micro additive manufacturing research

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Abstract

The design of experimental test parts to characterize micro additive manufacturing (AM) processes is challenging due to the influence of the manufacturing and metrology processes. This work builds on the lessons learned from a case study in the literature to derive generalized requirements and high level decompositions for the design of test parts and the design of experiments to characterize micro additive manufacturing processes. While the test parts and the experiments described are still work in progress, the generic requirements derived from them can serve as a starting point for the design of other micro additive manufacturing related studies and their decompositions can help structure future work.

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Keywords: Additive manufacturing; micro manufacturing; metrology; design of experiments; requirements; decomposition.

1. Introduction

Experiments to characterize, control, and optimize micro additive manufacturing (AM) processes require the design, production, and measurement of test samples with features whose characteristics (e.g. dimensions) vary based on the experimental conditions. Although this seems like a straightforward task, previous work [1] has shown that the design of micro AM test parts is strongly coupled to the manufacturing and the metrology processes in ways that can be difficult to predict. As a result, many of the design requirements are emergent.

This work builds on the lessons learned from the case study in [1] to derive generalized requirements for the design of test parts to characterize micro additive manufacturing processes. It begins with a brief overview of the case study and the requirements process in Axiomatic Design Theory. Next, it presents generic requirements and a high level decomposition for an experimental test part based on the findings from the case study. It is shown that the detailed design of the test features cannot be derived from test part requirements. The problem is then viewed from a design of experiments (DoE) perspective. The factors and responses for a generic micro AM experiment are defined. Next, the requirements and a high level decomposition for an experiment to determine the minimum printable feature size of an AM process are presented. The test part is further decomposed from a generic DoE perspective and for the one-factor-at-a-time strategy from the case study. The paper concludes with a discussion of the limitations of the experimental design and directions for future work.

2. Case study

This work is based on a set of three test parts (figure 1) that were developed to determine the minimum voxel size, and therefore resolution and precision, of a digital light projection (DLP) 3D printing process [1]. Each test part is a 10x10x5mm cube with a 20x20 grid of features on the top face. Each test part has features with one small variable dimension and two large fixed dimensions: Xx200x100μm ($5 \leq X \leq 100$μm), 200xYx100μm ($5 \leq Y \leq 100$μm), and 200x200xZμm ($5 \leq Z \leq 68$μm). A 0.5x0.75mm border surrounds and protects the feature sets. Small channels in the top left and bottom right

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corners of the border indicate the x and y axes of the part and can be used to orient the part (figure 2).

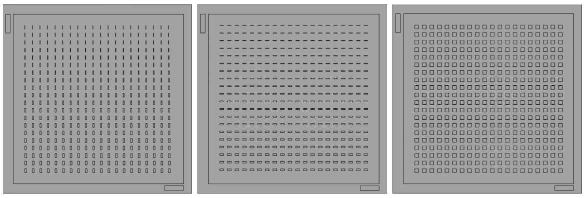

Fig. 1. Top view of the solid models for the full set of test parts: variation in x (left), variation in y (center), and variation in z (right)

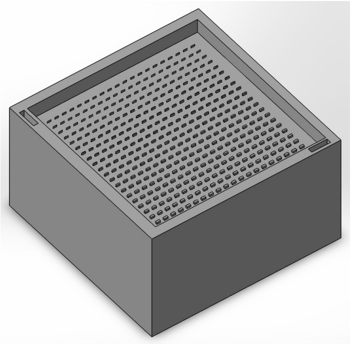

Fig. 2. Isotropic view of solid model for one of the test parts (variation in y)

3. The requirements process in Axiomatic Design Theory

The design process in classical Axiomatic Design Theory involves the definition of information within four domains (customer needs in the customer domain, functional requirements in the functional domain, design parameters in the physical domain, and process variables in the process domain) and the mapping of information between the domains. Constraints are defined with the functional requirements and influence the mapping and decomposition processes in the last three domains [2,3].

This work uses the extended model of the Axiomatic Design requirements process described in [4]. Stakeholders and their needs are identified. Next, the stakeholder needs (SNs) are translated into functional requirements, non-functional requirements, constraints, selection criteria, and optimization criteria [4,5]. Finally, the functional requirements are mapped to the design parameters and process variables, taking into account all of the requirements information.

4. Stakeholders and stakeholder needs

The stakeholders for test parts like the ones in the case study include the researchers who design and oversee the experiment(s), the production engineers who make the test parts, the metrology engineers who measure the test parts, the computer scientists who extract information from the measurement data to characterize the test part features (e.g. [6]), and the statisticians who aggregate and analyze the data. To facilitate the work of these stakeholders, the test parts should:

- SN1 – Provide information about micro AM processes
- SN2 – Be fast, easy, and inexpensive to make
- SN3 – Be fast, easy, and inexpensive to measure
- SN4 – Be easy to handle and store
- SN5 – Be possible to reuse and re-measure

In addition, the information derived from the test parts should:

- SN6 – Be representative
- SN7 – Be as independent from other factors as possible
- SN8 – Be easy to process (via image / data analysis)
- SN9 – Be suitable for statistical analysis
- SN10 – Have quantifiable uncertainties

As is often the case, these stakeholder needs are mostly a collection of non-functional requirements, selection criteria, and optimization criteria. While the SNs contain many hidden or latent needs, these are often only identified in retrospect. Many of the functional requirements and constraints can only be identified after some of the design decisions have already been made. For example, the metrology equipment cannot be chosen, and therefore the metrology-related constraints cannot be identified, until the feature geometry and material have been defined. This makes the requirements process, and therefore the entire design process, iterative.

5. High level decomposition for the test part

In the next two sections, we assume that the design artifact is the test part or a set of test parts. Each test part has one main functional requirement (FR1): to enable the study of micro additive manufacturing processes. This is an affordance [7] to be provided by the test features (DP1) rather than a true functional requirement.

For vat polymerization processes like DLP, micro scale test features can be created but unless they are printed (and therefore fixed) onto a larger test piece, they will be free to float in the resin where they can be lost or damaged. Even for processes where newly created voxels are held in place by gravity (e.g. powder bed fusion and binder jetting) or adhere to the working surface (e.g. material extrusion), micro scale features are hard to locate and manipulate. In addition, if they are moved or disturbed, the information about their printing orientation can be lost. This introduces a requirement to physically support the responses (features) and fix their location in space (FR2). This is achieved by printing the micro scale features onto a macro scale object (i.e. the test part base) (DP2).

The test features exist solely to be measured. In order to fulfill FR1, the test features must be protected from damage and other modifications until they are measured (FR3). If measurements must be done at regular intervals (for example, to determine the temporal stability of the features), then the features must also be protected between measurements. In the case study, the raised border (DP3a) protects the test features from damage if the test part is inverted. Other possible solutions include protective covers (DP3b) or special storage cases (DP3c).

The case study also identified the need to provide information about the parts and the test features (FR4) in order to improve usability. This can be done through signifiers [7] such features or labels on the printed part (DP4).

Based on this discussion, the highest-level decomposition for a micro AM test part can be defined as:

FR1 – Enable the investigation of AM processes
FR2 – Support and fix the test features
FR3 – Protect the test features
FR4 – Provide information about the part and test features

DP1 – Test features
DP2 – Test part base
DP3 – Test feature protection solution
DP4 – Features on / in the base / border

At the highest level, this design decomposition is physically integrated but effectively uncoupled if two conditions are met. First, the test features must be sufficiently far from each other and from other features on the test parts (e.g. the edges of the borders) to ensure that the creation of each test feature is independent [1]. Second, all structural elements of the test parts must withstand the routine forces encountered during production, measuring, handling, and storage. For example, the base of the test part must be thick enough to ensure that it does not bow and the border must be strong enough to ensure that the test features do not come into contact with other objects. This decomposition is generic and can be used as a starting point for the design of micro AM test pieces.

6. Initial constraints for the test part and their influence on the test part decomposition

The constraints for the test parts are derived from three main sources: the production equipment (i.e. the 3D printer to be studied), the stakeholders (i.e. the humans who will have to interact with the test part), and the metrology equipment (e.g. coordinate measuring machine, focus variation microscope, confocal microscope, atomic force microscope, etc.).

6.1. Constraints imposed by the production equipment

The production equipment is part of the problem definition. It can be thought of as a 0^{th} level constraint (C0). The production equipment adds two first level constraints to the design of the test part: it determines the materials that can be used and the maximum size of the test part:

C1 – The test part materials that can be used
C2 – The maximum build envelope for the test parts

These are system constraints, i.e. “constraints imposed by the system in which the design must function” [8]. They are also generic for all test parts.

The minimum layer thickness and the minimum feature size (i.e. the native voxel size) of the machine would usually be taken as constraints. However, for this research, they are the desired outputs of the study. Their estimated values can be used to set the upper and lower bounds of the test feature geometry but they cannot be taken as hard (or known) limits.

6.2. Usability constraints

Throughout the experimental process chain, researchers and engineers must handle the test parts. To maximize ease of use, the test parts should be large enough to pick up and move by hand. This places a constraint on the minimum size of the test part (C3).

C3 – The test parts should be large enough to handle without special equipment (vacuum wand, tweezers, etc.)

To measure the parts, the metrologist has to place the part in the machine in the correct orientation, locate the features to be measured, and then measure them. Measurement setup is faster and easier if the parts can be oriented with the naked eye (C4) and if the features are easy to find (C5).

C4 – It must be possible to orient the test parts with the naked eye
C5 – The metrologist must be able to easily identify where test features should be

Constraints C3 through C5 are input constraints, “imposed as part of the design specifications” [8]. They represent choices made by the designer and could be relaxed if necessary. These ‘constraints’ could also be interpreted as non-functional requirements: the part should be easy to handle without special equipment (nFR1) and the features should be easy to find (nFR2). Both interpretations lead to the same result: FR4 and DP4 must be decomposed to ensure that the part can be oriented and the features can be found. The second and third levels of FR4/DP4 from the case study are:

FR4.1 – Indicate correct orientation of the test part
FR4.2 – Indicate starting point of feature grid
    FR4.2.1 – Indicate starting point of feature grid in x
    FR4.2.2 – Indicate starting point of feature grid in y

DP.4.1 – Orthogonal channels in the border
DP.4.2 – Distance of feature array from border
    DP4.2.1 – Distance from left border to feature array
    DP4.2.2 - Distance from top border to feature array

This decomposition is not generic. It assumes that DP3 will be a raised border and that the geometry of the feature array (determined by the decomposition of FR1/DP1) will be a regularly spaced square array. The expected location of responses could also be indicated by placing a channel (DP4.2b) or border (DP4.2c) around each feature, by placing a channel (DP42d) or border (DP4.2e) around sets of features, by printing lines (DP4.2f) or arrows (DP4.2g) to indicate feature locations, or by any other printed feature.

6.3. Constraints imposed by the metrology equipment

The test features in the case study were measured using an Alicona InfiniteFocus G4 microscope. The operating principles of the Alicona add a number of constraints to the design space. Each measurement objective (5x, 10x, etc.) has a fixed measurement footprint and a range of lateral and vertical resolutions that can be used [9]. This sets limits on these measurement parameters (C6 – C9) and couples them to one another. Measurements with larger footprints can be performed through stitching operations. However, there is a practical limit to the size of data file that can be created (C10) [1]. Finally, the Alicona has a fixed working distance required for a given feature to be in focus (C11) and minimum and maximum measureable heights (C12) for a given objective [9]. This can place limitations on the test part geometry. For example, if the border is very tall and the test features are too close to the border, it may be impossible for the objective to get close enough to the features to measure them.

C6 – Maximum lateral resolution for a given objective
C7 – Maximum vertical resolution for a given objective
C8 – Maximum footprint that can be measured for a range of lateral resolutions
C9 – Maximum footprint that can be measured for a range of vertical resolutions
C10 – Maximum footprint that can be stitched for a range of lateral and vertical resolutions and a given feature height
C11 - Working distance for a given objective
C12 – Min / max measureable height for a given objective

6.4. Bounding the design parameters with constraints

This collection of constraints can be used to bound the dimensions of the various elements (design parameters) of the test parts. For example, the footprint of the test part must be larger than the footprint of the feature set and smaller than the printable footprint of the machine. Similarly, the total height of the test piece (base plus border) must be less than the total printable height of the machine (minus the height support layers or features if used). The border height must be larger than the height of the tallest feature but either short enough or far enough away from the test features that it does not interfere with measurement. And so on. The values of these design parameters can be fine-tuned using selection criteria (e.g. minimize print time, minimize cost, etc.).

The requirements identified above and the resulting decomposition allow dimensions for most of the bulk geometry of the test part to be chosen. However, these requirements tell us relatively little about the test features. Their design must be drawn from the operating principles of the additive manufacturing equipment and from classical design of experiments.

7. High level decomposition from a design of experiments perspective

In this section, we assume that the design artifact is an experiment to determine the minimum voxel size, and the resulting resolution and precision, of an additive manufacturing process. This moves the design problem to a higher level of abstraction and changes the requirements and the resulting decomposition.

7.1. Classical design of experiments

The main goal for the design of an experiment (or a series of experiments) is to create a response (y) or a series of responses (y_1, y_2, … y_i) that can be measured and analyzed in order to determine which controllable factors (i.e. input variables) (x_1, x_2, … x_i) and uncontrollable factors (z_1, z_2, … z_i) have an impact on the response(s), in what ranges the factors do and do not have an impact on the response(s), and how the factors interact with each other (figure 3). This information can then be used to determine which factors (x's and z's) have the most influence on the response y, where to set the influential x's to achieve or avoid a given value of y, to obtain an optimal value of y, and to reduce the variability of y [10].

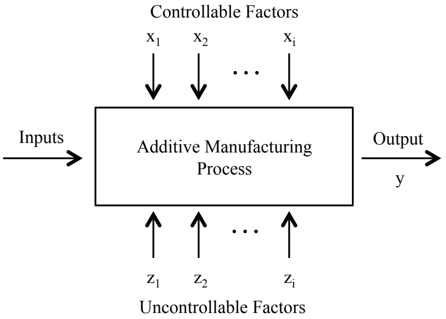

Fig. 3. Input/output model of a generic additive manufacturing process from a design of experiments perspective [Adapted from 10]

7.2. Factors and responses in micro additive manufacturing research

In micro additive manufacturing, the responses (y's) are the characteristics (e.g. dimensions) of the printed test features. The controllable inputs that affect the responses can be divided into three categories. The first set is composed of the test features (their specified dimensions, the number of each type of feature, the relative positioning and orientation of the features, etc.), which define the expected / desired outputs. These features can be used to identify the mean voxel size of the system, the voxel shape and dimensions, the voxel variance under a given set of conditions, and the overall precision of the system.

The second set of factors is composed of manufacturing process parameters (machine settings, postprocessing procedures, etc.) that can affect the test feature creation. Varying these factors will help to optimize and control the 3D printing process.

The third set of factors could be controlled but are fixed at values that effectively remove them from the experiment and the design matrix. In the case study, some of the test part dimensions (e.g. the spacing between the features), many of the test part dimensions (e.g. border thickness), most of the process parameters (e.g. print layer thickness), and all metrology variables (e.g. objective, vertical and lateral resolution, etc.) fall into this category.

The uncontrollable inputs include manufacturing process parameters that cannot be set by the user, the composition and associated variability in the quality of commercial materials, environmental conditions, human error, and more.

7.3. High level decomposition for micro additive manufacturing design of experiments

The high level decomposition for micro additive manufacturing design of experiments is similar to the decomposition for the test parts with a few exceptions. In micro additive manufacturing research, the goal is to obtain responses (FR1) from the manufacturing process given a set of design and manufacturing inputs. This is a true FR and not an affordance. In addition, an experiment must measure (FR5) and interpret (FR6) the responses. Based on this discussion, the high level decomposition for a micro additive manufacturing experiment can be defined as:

FR1 – Obtain responses for the factors and combinations of factors of interest
FR2 – Support the responses and fix their location in space
FR3 – Protect (the integrity of) the responses
FR4 – Provide information about the part and test features
  FR4.1 – Indicate the correct orientation of the test part
  FR4.2 – Indicate the expected physical locations of the responses
  FR4.3 – Provide other information about the expected responses
FR5 – Measure the responses
FR6 – Interpret the responses

DP1 – Test features
DP2 – Test part base
DP3 – Test feature protection solution (e.g. raised border)
DP4 – Test feature signifiers
  DP4.1 – Features to signify part orientation
  DP4.2 – Features to signify test feature location
  DP4.3 – Other signifying features
DP5 – Metrology equipment and procedures
DP6 – Image / data analysis procedures

This decomposition is generic and can be used as a starting point for the design of experiments to determine the resolution of micro AM processes.

7.4. High level design matrix for micro additive manufacturing design of experiments

By default, the design matrix for the decomposition in section 7.3 should be decoupled (figure 4). The test part base (DP2) must be large enough to accommodate the test features (DP1). The feature protection system (DP3) must take into account the geometry of the test features (DP1) and the test part base (DP2). The information relayed by the signifiers (DP4) depends on the test feature design (DP1) and the manner in which it is relayed depends on the test part base (DP2) and the protection system (DP3). The measurement procedure (DP5) needs to measure the test features (DP1) while taking into account the constraints imposed by the geometry of the test part (DP2), the protection system (DP3), and the signifiers (DP4). Finally, the data analysis procedure (DP6) must take into account the test feature geometry (DP1) and the metrology procedure (DP5).

If the DPs are well chosen, the coupling between the DPs in this design matrix should be relatively weak and the design should be robust. For example, small changes in the test feature shapes or dimensions should not affect other aspects of the design. The weakly coupled off-diagonal terms in the design matrix are shown with small x's. The strongly coupled terms along the diagonal are shown with large X's.

$$\begin{pmatrix} \text{FR1} \\ \text{FR2} \\ \text{FR3} \\ \text{FR4} \\ \text{FR41} \\ \text{FR42} \\ \text{FR43} \\ \text{FR5} \\ \text{FR6} \end{pmatrix} = \begin{array}{|c|c|c|c|c|c|c|c|c|} \hline X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \hline x & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \hline x & x & X & 0 & 0 & 0 & 0 & 0 & 0 \\ \hline x & x & x & X & & & & 0 & 0 \\ \hline x & x & x & & X & 0 & 0 & 0 & 0 \\ \hline x & x & x & & 0 & X & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & & 0 & 0 & X & 0 & 0 \\ \hline x & x & x & x & x & x & 0 & X & 0 \\ \hline x & 0 & 0 & 0 & 0 & 0 & 0 & x & X \\ \hline \end{array} \begin{pmatrix} \text{DP1} \\ \text{DP2} \\ \text{DP3} \\ \text{DP4} \\ \text{DP41} \\ \text{DP42} \\ \text{DP43} \\ \text{DP5} \\ \text{DP6} \end{pmatrix}$$

Fig. 4. Design matrix for a generic decomposition of a micro additive manufacturing experiment

7.5. Requirements and constraints for test features and feature arrays

To ensure that the data from the experiment can be used, the analysis must return response values that are representative of the phenomena (C13). To be able to draw conclusions, a measure of the response variance (C14), a measure of the response uncertainty (including measurement uncertainty) (C15), and confidence intervals for level of significant tests (C16) are also needed.

C13 – The response value(s) must be representative of the phenomena
C14 – The analysis must return a measure of response variance
C15 – The analysis must return a measure of response uncertainty
C16 – The number of observations must permit conclusions to be drawn at a given level of confidence

This collection of constraints has implications for the decomposition of FR1 (the design of the test features) as well as the decompositions for FR5 and FR6 (the design of the measurement and analysis procedures). For example, C14 requires at least 3 observations per measurement so a standard deviation can be calculated. C16 requires a power analysis to ensure that the number of observations is sufficient for the required or chosen confidence level. C13 requires invalid or potentially invalid observations (i.e. outliers) to be identified and removed from the data set. C15 requires an uncertainty budget to be calculated.

7.6. Generic decomposition of test features and feature arrays

The decomposition of FR1 depends on the strategies used for the design of the experiment (e.g. best guess, one-at-a-time, factorial design, etc.). A generic decomposition might include one design parameter for the expected shape of the test features (cube, cylinder, etc.) and one design parameter for each characteristic dimension to vary (e.g. one length for a cube, a length and a diameter for a cylinder, etc.). It might also include design parameters for the number of factors to study and the number of values per factor (e.g. 3 and 2 for a 3^2 factorial design). This will determine the total number of combinations in the study. Finally, it would need DPs for the number of observations per combination and the number of times to repeat the experiment (if desired).

7.7. Decomposition using a one-at-a-time approach

The case study used a one-at-a-time approach for the test features. It was assumed that the voxel geometry could be described by 3 factors. Each factor had 20 input values. Each value was observed 20 times. Therefore, the x and y test parts could be described by 5 design parameters: the factor to vary, the starting value of the factor to be varied (5μm), the interval between values (5μm), the number of observations (features) per value (20), and the total number of values (20). The decomposition for the z samples is more complicated because it did not have a constant interval between values. For a more generic decomposition of a one-at-a-time strategy, each test part needs two DPs per factor value (the value itself and the number of observations for that value). A partial decomposition for the case study test parts is shown below:

FR1 – Obtain responses for the factors related to the x, y, and z resolution of a DLP 3D printing process
  FR1.1 – Obtain responses for a range of input lengths in x
    FR1.1.1 – Obtain response for 1st input length
      FR1.1.1.1 – Obtain response for input length #1
      FR1.1.1.2 – Obtain response variance
  ⋮
    FR1.1.20 – Obtain response for 20th input length
      FR1.1.20.1 – Obtain response for input length #20
      FR1.1.20.2 – Obtain response variance
  FR1.2 – Obtain responses for a range of input lengths in y
  FR1.3 – Obtain responses for a range of input heights in z

DP1 – Set of three test parts, each with a test feature set
  DP1.1 – x sample test feature set
    DP1.1.1 – 1st row of test features
      DP1.1.1.1 – 5μm
      DP1.1.1.2 – 20 features
  ⋮
    DP1.1.20 – Last row of test features
      DP1.1.20.1 – 100μm
      DP1.1.20.2 – 20 features
  DP1.2 – y sample test feature set
  DP1.3 – z sample test feature set

Each manufacturing process factor adds one level per factor to the decomposition: For example:

FR1 – Obtain responses for the factors related to the x, y, and z resolution of a DLP 3D printing process for a range of materials
  FR1.1 – Obtain responses w/ process parameter 1 value 1
    FR1.1.1 – … for a range of input lengths in x
      FR1.1.1.1 – Obtain response for 1st input length
        FR1.1.1.1.1 – Obtain response for input #1
        FR1.1.1.1.2 – Obtain response variance
  ⋮
  FR1.2 – Obtain responses w/ process parameter 1 value 2
  FR1.3 – Obtain responses w/ process parameter 1 value 3

These decompositions are uncoupled.

7.8. Decomposition of FR7

For the overall experiment, DPs are also needed to describe the repetitions that will ensure the validity of the experiment and to determine the impact of the uncontrollable factors. For example, the designer must specify the number of each test parts per print job and the number of print jobs for each set of factors. A more detailed discussion of FR7 is beyond the scope of this work.

8. Discussion and Limitations

The design of the test features and the experiment from the case study are by no means optimal. For example, the test feature design assumes that the DLP system produces cuboid voxels in a Cartesian coordinate system that is aligned with the design and printing coordinate systems. These assumptions may not be (and likely are not) true. The current test part design does not consider and therefore cannot quantify spatial variations in voxel production. And, while the test features are spaced to reduce interaction, all features on the test part are physically integrated and therefore physically linked. Thus, the test features cannot be fully independent of each other. In addition, neither the test parts nor the experiment provide any information about the presence or nature of interaction between the various factors under consideration. To address these limitations, the test features and/or test parts would need to be redesigned and more advanced statistical strategies, such as randomization and blocking in a factorial design, would need to be employed.

9. Conclusions

This work derived requirements and presented generic high level decompositions for a test part and the design of experiments to determine the minimum printable feature size for additive manufacturing processes. It was shown that the experiment must collect, measure, and interpret responses to a given set of factors, while the test parts must support and protect the responses and provide information to users. The design of the test parts and the experiment are subject to constraints from the manufacturing process, usability and ergonomic considerations, the metrology equipment, and the data analysis procedure. While the test parts and the experiment in the case study are still work in progress, the generic requirements derived from them can serve as a starting point for the design of other micro additive manufacturing related studies and their decompositions can help structure future work.

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