A Multi-Material Part Design Framework in Additive Manufacturing

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ABSTRACT

Additive manufacturing (AM) technologies provide more freedom to functional part design in various industries. One of the unique capabilities of AM is that multi-material parts can be produced with material compositional and geometric complexity. Multi-material parts have the advantage of achieving multiple performance requirements. In the research, we propose a framework for designing multi-material parts using AM processes. The proposed framework is composed of four interacting modules, including design requirement identification, primary material selection, AM process selection, material composition and part geometry determination. Rules and guidelines for AM are integrated into the proposed framework with AM processes' capabilities and constraints compiled in databases. We also introduce databases to assist in decision-making and ensure manufacturability of the designed multi-material part in various product design phases. The proposed framework is applied to a case study involving a conceptual design of a multi-material battery pack cooling plate.

KEYWORDS

Additive manufacturing, Design for AM, Design methods, Multi-materials

1. INTRODUCTION

With the unique capabilities in fabricating products with high complexity in shape, function, and material, additive manufacturing (AM) technologies have greatly increased design freedom in product development and customization [1,2]. Special AM design features such as cellular structures, topology optimized structures, and integrated joints have been introduced as new design freedoms for products' performance enhancement [3]. Maidin et al. [4] constructed an AM design feature database which allowed designers to view the information about design feature geometries and applications in the conceptual design stage. Constraints and rules, such as material selections and dimensional limitations [5], should also be considered during the design for additive manufacturing (DfAM) practices in order to ensure the part's manufacturability in AM processes [6].

Some AM processes have the capability to fabricate multi-material parts, which consist two or more dissimilar materials distributed in the part's volume with a designed composition or architecture [7]. A multi-material part has the advantage of achieving multiple functionalities; and its performance can be enhanced through proper design of material compositions and part geometries. In the research of Oxman [8], the concept of "variable property rapid prototyping (VPRP)" was proposed to represent bio-inspired structures that had heterogeneous material compositions to achieve multi-functionality. The VPRP concept was illustrated by an additive manufactured multi-material glove for Carpal Tunnel Syndrome patients. Combining soft and hard materials in different locations, the glove was able to provide cushioning and restrict the patient's palm movement at the same time.

In this study, a framework is proposed for systematic multi-material part design facilitated by multi-material additive manufacturing (MMAM). The proposed framework is composed of four interacting modules: (1) product functional and technical requirement identification, (2) primary material selection, (3) MMAM process selection, and (4) material composition and part geometry determination. The proposed framework aims to introduce a systematic approach for designers to organize complex material and machine-related resources in their designing process. Design objectives can be achieved by appropriate decisions made at each stage of the framework.

In this paper, Section 2 presents literature review related to multi-material AM processes and multi-material design. Section 3 explains the individual modules in the proposed design framework. In Section 4, a case study in the conceptual design of a battery pack cooling plate is discussed to demonstrate the multi-material design concept enabled by MMAM. Conclusions and future work are discussed in Section 5.

2. LITERATURE REVIEW

Multi-material fabrication can be achieved by a variety of additive manufacturing processes, as summarized below. Laser engineered net shaping (LENS) process has been applied to build functionally graded metal parts such as the combination of stainless steel 316L and Stellite Grade 12 Co-Cr alloy [9]. Either continuous or sharp/discrete compositional gradient could be made in periodic multilayered structures, and the transition zone thickness was controllable by process variables. In the work of Muller et al. [10], powder flow rate was modeled by a first order transfer function, and was controlled using a PI controller. Therefore, material composition in each layer could be adjusted by varying powder flow rate of different primary materials. Three Dimensional Printing (3DP) is a binder jetting AM process that can be used to build multi-material parts. The multi-material composition is achieved by controlling binder concentration which affects mechanical properties of the part [11]. However, in multi-material 3DP processes, the powder bed is usually composed of a single type of material. Material extrusion AM processes, such as fused deposition modeling (FDM), can build multi-material parts by applying multiple extruders (nozzles) concurrently, each of which prints a different material [12]. A special type of multi-material FDM process utilizes a nozzle extruding a dissolvable support material and a separate nozzle extruding the actual model material. Although ceramics and wax can also be processed using multi-material FDM [13], thermal-plastic polymers are still the most common stock materials in most commercial FDM machines. Ultrasonic consolidation (UC) has been shown to be able to print multi-materials, using Al-alloys, Ni-alloys, stainless steels, and many other metallic materials as well as fiber-reinforced metal matrix composites [14]. Multi-material fabrication using Polyjet processes has recently been achieved, with the capability to print multiple types of resins within a single part [15]. A key advantage of the multi-material Polyjet is its capability to mix various resins in arbitrary compositions on the voxel level, enabling a large number of different colors or properties in the part. In the process of shape deposition manufacturing (SDM), individual layer segments are deposited then accurately machined to net shape before depositing additional material. At appropriate layers, discrete components with different materials can be placed on top of the current surface before subsequent deposition takes place [16]. AM machine manufacturers started to add multi-material fabrication capabilities into existing AM processes only in recent years [10,13,12,15,17], therefore a lot of challenges still remain for industrial applications, including material mixing and deposition accuracy, dissimilar material bonding mechanisms, concurrent process monitoring and feedback for different source materials, product reliability and quality assurance.

Modeling and representation methods of multi-material objects have been studied by proposed in literature. For example, in the work of Bhashyam et al. [18], a CAD system was developed for creating “heterogeneous objects” that can contain multiple materials. A heterogeneous object was mathematically represented using the r_m-object framework, and the heterogeneous solid modeler was implemented in C++ using the ACIS kernel. Design methods of multi-material parts have been studied in some previous research. According to Shin et al. [19], two general approaches could be applied to multi-material part design. The first one was the Generative Approach, in which geometry and material distributions are simultaneously optimized using algorithms such as Homogenization Design Method (HDM) [20]. The second one was the knowledge-based Variant Approach in which designers could apply their creativity and personal experience more freely. Wargnier et al. [7] proposed a conceptual procedure for multi-material design, with the emphasis on material searching. In the above work, material searching was done preliminary by categorizing functional requirements followed by applying screening tools. However, manufacturing processes for multi-material fabrication were not discussed, and hence Design for Manufacturing (DfM) rules were not taken into consideration in the proposed procedure.

In this research, we propose a design framework for multi-material parts built by additive manufacturing. The proposed framework attempts to combine multi-material selection and design procedure along with MMAM capabilities and constraints into one integrated design for additive manufacturing (DfAM) system, aiming to assist designers in exploiting new design freedoms in AM.

3. DESIGN FOR MULTI-MATERIAL IN ADDITIVE MANUFACTURING FRAMEWORK

The proposed design for multi-material in additive manufacturing (DfMAM) framework is composed of four interacting modules. The flowchart of the DfMAM framework is represented in Fig 1. Designers start the design process by identifying functional requirements and corresponding technical requirements obtained from customers. In the "primary material selection" module, candidate primary materials are chosen from AM material databases to achieve multiple design requirements. The appropriate AM processes are then selected to fabricate the product with previously chosen materials, and corresponding DfAM rules are extracted from the process database. In the final step, material composition and part geometry are designed to achieve functional requirements while complying with DfAM rules to ensure manufacturability. The dashed lines in Fig 1 indicate iterations in primary material and MMAM process selection when the detailed product design (in Module 4) cannot generate satisfactory results. In the next sections, the interacting modules of the proposed DfMAM framework are discussed in details.

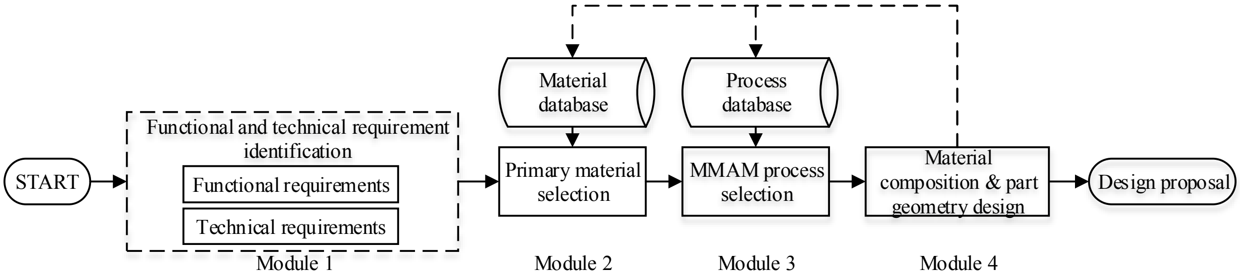

Fig 1: The flowchart of the proposed DfMAM framework

3.1. MODULE 1 – FUNCTIONAL AND TECHNICAL REQUIREMENT IDENTIFICATION

The first stage in multi-material part design is to identify functional requirements of the parts. In general, market surveys or economic analysis can be conducted to acquire customer voice that indicate the functional requirement of the product. And then functional analysis is followed to translate the functional requirement into more specific technical requirements [21] that are fulfilled by proper designs. Analytical tools such as quality function deployment (QFD) can be applied to analyzing functional requirements [22]. For example, functional and technical requirements for a car engine casing are identified and represented by QFD as shown in Table 1, where the ● mark indicates strong relationship, ○ mark indicates moderation relationship, and ▽ mark indicates weak relationship. In the QFD method, the technical requirements with the ● marks in the columns are the major design objectives that need to be achieved by selecting appropriate materials (or multi-material compositions) and part geometries. When multiple different technical requirements coexist in the design problem, a multi-material part may have a higher chance to succeed than a single-component par.

Table 1: Functional and technical requirements of a car engine casing

Technical Requirements Functional requirements	High fatigue resistance	High thermal conductivity	Light-weight structure	Light-weight material	Low raw material cost	Low manufacturing cost	Compact size
Long lifecycle	●	▽	▽	▽	▽	▽	▽
Efficient cooling	▽	●	▽	▽	▽	▽	▽
Low fuel consumption	▽	○	●	●	▽	▽	●
Suitable for mass production	▽	▽	▽	○	●	●	▽

3.2. MODULE 2 – PRIMARY MATERIAL SELECTION

In multi-material part design, each technical requirement generated in Module 1 may be satisfied by an individual material separately which is to be integrated with other primary materials into the final product. Therefore, the material selection process for multi-material parts has more freedom than that for mono-material parts. However, extra constraints specific to multi-material part design should be considered in primary material selection. One such consideration is the mutual compatibility of dissimilar materials which are to be bonded to form an integrated part. Only materials with well bonded interface can be determined as suitable primary materials. Therefore, the mutual compatibility test can serve as a filter in the material selection.

A QFD-based approach has been applied to material selection decision-making process for mono-material products [22]. This approach outputs a ranking of the shortlisted materials using a scoring system, based on material properties that can meet technical requirements. In the proposed design framework, the QFD-based ranking method is extended to select primary materials in multi-material parts. Being different from the original method in [22], the modified method separates technical requirements into groups, and then each group is used as an independent criteria to search for suitable materials. In this manner, multiple groups of technical requirements will output multiple candidate primary materials. This process is summarized in Fig 2.

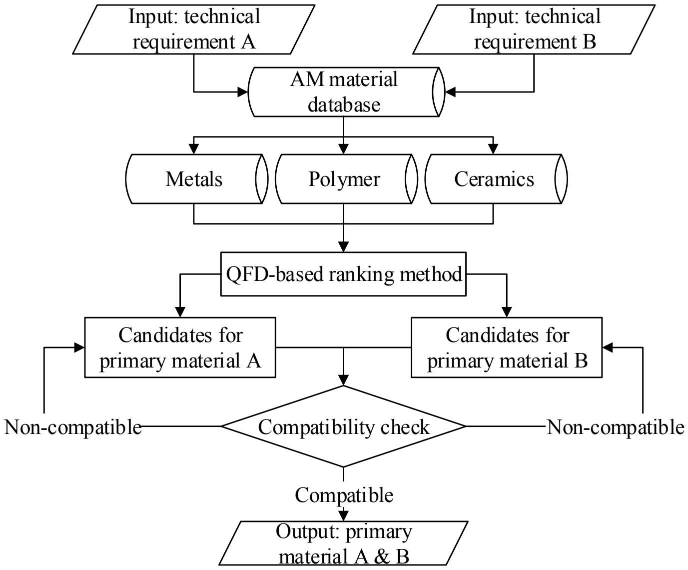

Fig 2: Primary material selection module

Candidate primary materials must be selected from the pool of materials that can be processed by MMAM techniques. An AM-specific material database is required for the selection. The database can be organized based on material families [23], due to the fact that each different AM technique can process only a limited number of families of materials.

In some cases, the use of the one material in the product may compromise the product performance created by the other primary material, and this tradeoff effect must be taken into account in material selection for multi-material parts. In the example of a multi-material pressure vessel [19] made of metals and ceramics, the use of ceramics at inner layers may deteriorate the mechanical strength of the metal main body, and the metal-ceramics interface may also introduce high interfacial stress under temperature fluctuation. Therefore, evaluations need to be performed to justify the primary selection. Some of these problems may be resolved by choosing proper material composition functions and part geometry, which will be discussed further in the next section.

3.3. MODULE 3 – MMAM PROCESS SELECTION

Various MMAM processes have been developed. Direct energy deposition processes have been applied to build functionally graded metal parts, with either continuous or discrete compositional gradient [9]. Binder jet processes can be used to achieve multi-material compositions by applying different binders within the part volume [11].

Extrusion-based processes can build multi-material parts using multiple extruders [12]. The multi-material polyjet process has recently been developed to print different resins in the same part [15].

After the selection of primary materials in Module 2, the next step is to identify suitable MMAM processes. During the selection, designers should consider the capabilities and constraints of each candidate process in handling individual primary material. The MMAM processes selection module is represented in Fig 3.

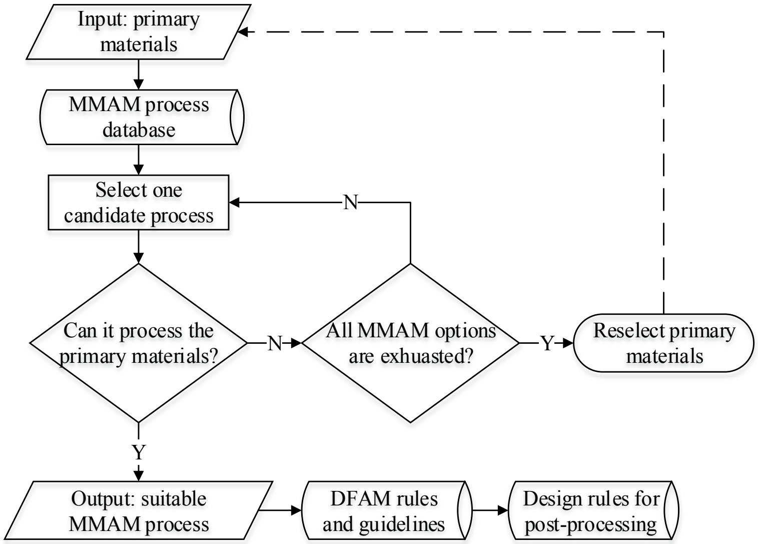

Fig 3: MMAM process selection module

All MMAM processes along with their technical specifications are organized in the database. To select the suitable MMAM process from this database, the first criteria is that the candidate process must be able to handle the chosen primary materials. If all the MMAM processes in the database are found incapable to process the primary materials and/or forming bond between them, the primary materials should be re-selected.

DfAM guidelines are incorporated in this module. These guidelines can be formulated using methods in previous literatures, such as the Benchmarking Features Flowchart in [24]. The guidelines for each MMAM process can be organized in a database which serves as an input to the next module of determining material composition and part geometry. An important design consideration is the design for easy and inexpensive post-processing, which is usually a separate process from the selected MMAM process such as support removal, polishing, coating, and various types of heat treatment [25]. The post-processing step influences the final quality of the product; hence it is also an important criterion in MMAM selection.

3.4. MODULE 4 – MATERIAL COMPOSITION AND PART GEOMETRY DETERMINATION

The multi-material compositions and part geometries must be designed by following process-specific constraints. As an example, Tables 2 and 3 list the compositional limitations and geometric constraints of different MMAM processes respectively.

Table 2: Material composition limitations of LENS and FDM

MMAM process	Material type	Varying material composition within layer	Varying material composition across layers	Deposition of multiple materials simultaneously	Continuous material gradient	Discrete material gradient
LENS	Metals	Yes	Yes	Yes	Yes	Yes
FDM	Thermosets	Yes	Yes	No	No	Yes

Table 3: Geometric constraints of SLM and FDM

MMAP process	Min hole diameter	Min wall thickness	Max vertical hole diameter	Max build envelope	Min overhang angle	Support structure
SLM	Between 1.5 and 2.5mm	0.6mm	6mm	250mm x 250mm x 325mm	Fe-alloy: 30° CoCr-alloy: 30° Ni-alloy: 45° Ti-alloy: 20-30° Al-alloy: 45°	Yes
FDM	0.8mm	0.4mm	1.4mm	200mm x 200mm x 200mm	60°	Yes

The multi-material composition design procedure is shown in Fig 4. The design process starts with reviewing the technical requirements. For MMAM processes that can only build parts with discrete material gradient, the part can be considered an assembly of various discrete sub-volumes each of which is made of a single material, and hence the design parameters in material composition design are merely the locations and sizes of these sub-volumes. An example is the sandwich layered structure in which the thickness of each layer is the design parameter. For MMAM processes that can create continuous material gradient, the material composition function needs to be proposed or selected from a library [18]. Selection of the material composition function is based on the target application. The parameters in the function have to comply with the design constraints of the selected MMAM process, since the rate of material composition variation is often limited by a material deposition control mechanism [10].

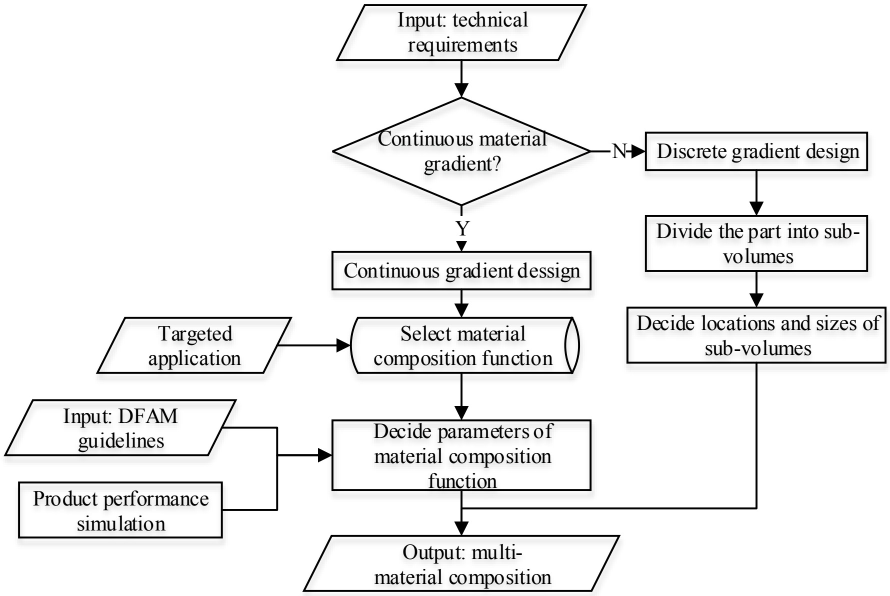

Fig 4: The multi-material composition design procedure

For multi-material parts, geometry design and material composition design are not two standalone procedures. An interactive approach is proposed to combine this two design tasks, and to make the product manufacturable. The interaction between material composition design and part geometry design is shown in Fig 5. After the part geometry design has been proposed, designers need to select portions within the part where multi-material composition is going to be deployed. Dimensional features (e.g. volume, thickness, fillet radius, overhang angle etc.) are extracted from the multi-material portions, which are then checked against DfAM rules (such as those shown in Tables 2 and 3) to ensure manufacturability.

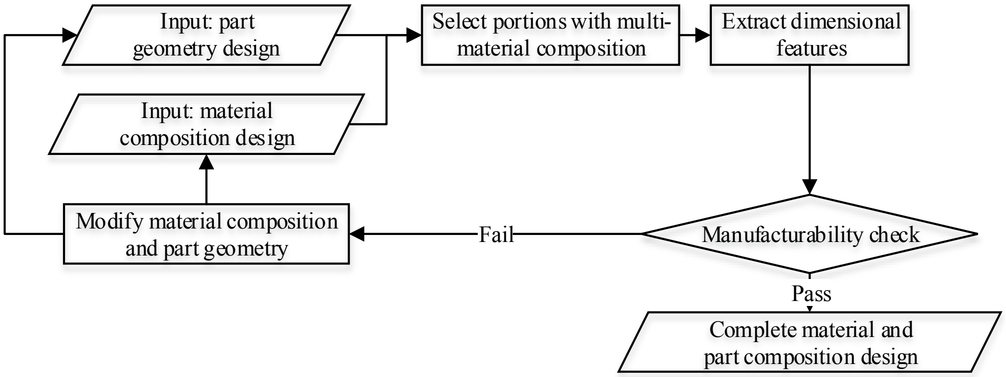

Fig 5: Interaction between part geometry and material composition design

4. CASE STUDY

The proposed DfMAM framework is illustrated in the case study of designing a cooling plate used in electric vehicle battery packs. As the power source of electric vehicles, prismatic Li-ion battery cells are usually stacked in a battery pack to generate sufficient voltage [26]. Efficient thermal management is crucial for the battery's lifetime and operation consistency. The battery pack has to keep its temperature below 40°C to ensure safety and durability of Li-ion batteries [27]. Therefore, cooling plates need to be placed between battery cells to transport heat away from them [28]. In addition, mechanical strength and weight are also important design concerns for battery packs. Current cooling plates are usually made of thin metal or highly thermal conductive plastics.

In this case study, a conceptual design of multi-material battery pack cooling plate is introduced to meet both performance and safety requirements. The steps of the multi-material part design framework introduced in Section 3 are followed during the cooling plate design process, as explained below.

4.1. STEP 1: FUNCTIONAL AND TECHNICAL REQUIREMENT IDENTIFICATION

Functional and technical requirements are determined by interviewing field experts in the electric-car racing team. Identified design requirements are listed in Table 4, where the ● mark indicates strong relationship, ○ mark indicates moderation relationship, and ▽ mark indicates weak relationship.

Table 4: Functional and technical requirements of a multi-material battery pack cooling plate

Technical Requirements Functional requirements	High thermal conductivity of material	Large contact area with coolant	Light-weight material	Light-weight structure	Small thermal expansion	Small internal stress	High impact strength of material	Impact energy absorbing structure
Efficient cooling	●	●	▽	●	▽	▽	▽	▽
Light-weight	▽	▽	●	●	▽	▽	▽	▽
Maintain structural integrity during normal operation	▽	▽	▽	▽	●	●	○	○
Resistant to accidental impact	▽	▽	▽	▽	▽	▽	●	●

4.2. STEP 2: PRIMARY MATERIAL SELECTION

We tried to fulfill the above design requirements by selecting proper primary materials. The candidate materials are listed in Fig 6. Based on the discussion in Section 4.1, the key property requirements of materials are high thermal conductivity, low density, and high strength. In this case study of the battery pack cooling plate, we consider only metallic materials since they provide better cooling efficiency than plastics or ceramics, and hence are the conventional materials for most heat exchangers. Using the QFD-based ranking approach introduced in Section 3.2, the initial selected materials are Cu-alloy (for higher thermal conductivity), Mg-alloy (for low density), and steel (for high strength). However, Mg-alloy is currently not a commercially available standard AM material due to its high activity. Furthermore, during the compatibility check as described in Section 3.2, Mg-alloy is not compatible to Cu-alloy or steel in AM. Therefore, we replaced Mg-alloy with the next best option in the “low density” category, i.e. Al-alloy.

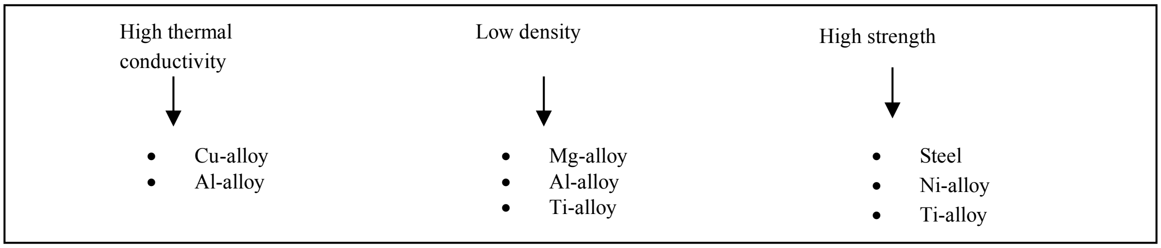

Fig 6: Candidate materials for battery pack cooling plates

4.3. STEP 3: MMAM PROCESS SELECTION

At the MMAM process selection stage, capabilities and limitations of each candidate process are extracted from the database. Since the selected primary materials are metal alloys, the candidate processes must be able to produce fully-dense metal parts with sound metallurgic bonding. Some of such processes are:

- Selective laser melting (SLM)
- Laser engineered net shaping (LENS)
- Shape deposition manufacturing (SDM)
- Ultrasonic consolidation (UC)

LENS is capable to produce multi-materials with continuous gradient within and cross layers. However, parts made by LENS require multiple steps of post-processing to achieve desired shape and dimensions. SDM and SLM can only create discrete material gradient. SDM process combines both additive and subtractive processes and hence SDM can achieve good dimensional accuracy and surface finish without much post-processing. UC can be applied to bond multiple pre-built layers in dissimilar materials, but it is not able to create individual layers by direct powder or filament deposition. The bond strength between dissimilar materials in SLM is still an unknown issue due to lack of published research result. Geometry and material composition design are performed concurrently. The overall dimension of the cooling plate will not be changed from the existing design, due to the dimensional constraint of battery unit cells and the battery compartment in the vehicle. For demonstration purpose, a simple prismatic plate of 5mm thick is taken as the design reference. Cooling channels are embedded. Al-alloy is chosen as the main primary material for the cooling plate, with a relatively small amount of Cu-alloy applied in the area near the inner wall of cooling channels.

As described in Section 3.3, DfAM design rules and guidelines of the LENS process are retrieved from the database and used in the part geometry design process. For the case of battery pack cooling plate design, important DfAM rules include the maximum plate size (restricted by the machine's maximum build envelope) and the minimum plate thickness (restricted by the minimum printable track width by the LENS nozzle). Post-processing rules also should be considered in part design. In the LENS process where high thermal stress is caused by laser induced rapid solidification, as-printed parts will inevitably have distortions which need to be compensated by post-machining. In addition, the rough surface of parts made by the LENS process need to be grinded to achieve the desired surface finish. Therefore, sufficient stock (usually more than 1mm) should be added to the part's designed dimensions as the machining allowance.

4.4. STEP 4: MATERIAL COMPOSITION AND PART GEOMETRY DETERMINATION

Based on the requirement of avoiding sharp mismatch of thermal expansion rates, a continuous material gradient is desired at the Al-Cu transition. The material composition functions can either be selected from the library for specific applications or proposed by the designer. Using the approach from [29], the temperature distribution in an aluminum cooling plate under the operation condition can be simulated. Although the result from [29] is based on a single material part, it can help designers understand the heat transfer behavior within the cooling plate. It can be found that the portion with the highest temperature is the lower-right corner, which locates the inlet channel. This portion can be made of mainly Cu-alloy which has higher thermal conductivity, while the left portion near the outlet channel can be made of mainly Al-alloy with slightly lower thermal conductivity but less weight.

A 2D material composition pattern on the x-z plane is hence proposed in Fig 7. The dash lines are normal to the gradient of material composition variation. LENS is chosen as the MMAM process for the fabrication of one sheet of such panel due to its capability to vary material input ratio within one layer. LENS is also capable to create internal cooling channels within the plate.

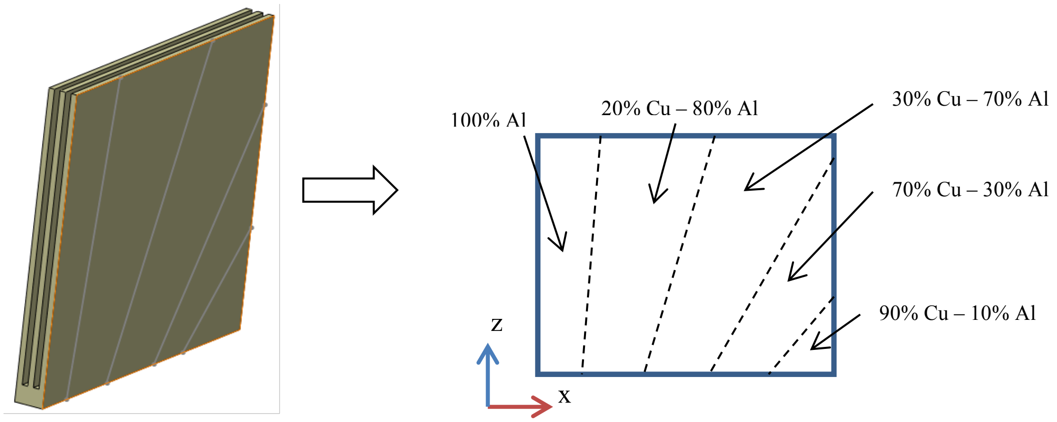

Fig 7: The cooling plate's multi-material compositoin on the x-z plane

In a separate design, material composition can also be varied along the *y* direction. To achieve the functional requirement of high impact strength, harder materials can be applied to the outer layers of the plate. The material variation along *y* direction is shown in Fig 8. Continuous composition gradient is not required across layers. Therefore, the cooling plate can be deposited by LENS in a whole piece, or can be made by stacking and bonding several pre-built layers using UC. Most commercial UC machines have built-in CNC modules to achieve high dimensional accuracy and fine surface finishing. Hence UC is preferred over LENS in the cooling plate fabrication.

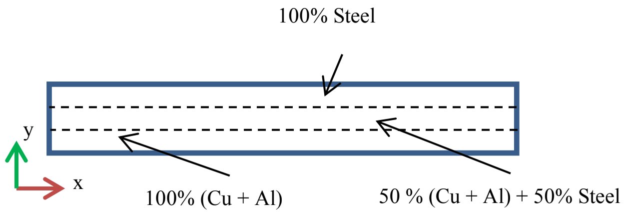

Fig 8: The cooling plate's material composition along the *y* direction

As illustrated in the case study of conceptual design for a battery pack cooling panel, the proposed DfMAM framework was able to guide designers through various tasks during the design process for additive manufactured multi-material parts. Various information/resources about materials and AM processes are coordinated in the conceptual design process in an orderly manner. Based on the proposed design concepts, more details can be added to achieve desired performance and manufacturability.

5. CONCLUSIONS

In this research, we proposed design for multi-material in additive manufacturing (DfMAM) framework based on the information of additive manufacturing resources, including processes, materials, and design constraints. The proposed DfMAM framework integrates four modules: (1) functional and technical requirement identification, (2) primary material selection, (3) MMAM process selection, and (4) material composition and part geometry determination. A case study in designing a battery pack cooling plate was conducted to demonstrate the multi-material design concept. The proposed DfMAM framework can guide designers in exploiting the design freedoms brought by additive manufacturing.

The present study is at the early stage of exploring a general method for multi-material part design, while the major limitation is the lack of specific design rules for each specific multi-material additive manufacturing process. Therefore, in future work, more in-depth investigation of capability and constraints of multi-material part design in specific AM process will be conducted. And then, a design optimization method may be formulated to search for the best combinations of material compositions and part geometries. In this paper, the case study in multi-material cooling plate design is still at the conceptual design level. Future studies can focus on more specific topics, such as property/performance simulation methods for multi-material parts, computer-aided design (CAD) software with multi-material part design capability, and multidisciplinary design optimization for multi-material parts with multi-functionalities.

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