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STEP-NC Process Planning for Powder Bed Fusion Additive Manufacturing

Powder bed fusion (PBF) is an additive manufacturing (AM) technology that uses high-power beams to fuse powder material into layers of scanned patterns, thus producing parts with great geometric complexity. For PBF, the selection of appropriate process parameters, environmental control, and machine functions play critical roles in maintaining fabrication consistency and reducing potential part defects such as cracks and pores. However, poor data representations in the form of approximated geometry and incoherent process plans can negatively impact the relationship between the selected parameters. To address this issue, the Standard for the Exchange of Product model data Numerical Control (STEP-NC) recently added standardized data entities and attributes specifically for AM applications. Yet, the current STEP-NC data representations for AM do not have definitions for process parameters and scan strategies that are commonly used in PBF processes. Therefore, there is a need for defining data models that link process parameters with process control. To bridge this gap, in this paper, an amended STEP-NC compliant data representation for PBF in AM is proposed. Specifically, the characteristics of the interlayer relationships in PBF, along with the technology and scan strategy controls, are defined. Simulation results demonstrate the feasibility of granular process planning control and the potential for producing high-quality parts that meet geometric requirements and tight tolerances. The contributions of this paper highlight the importance of information models in AM, promoting data representations as key enablers of the AM technology and supporting the neutrality and interoperability of data across AM systems.
[DOI: 10.1115/1.4055855]

Keywords: computational foundations for additive manufacturing, data-driven engineering, engineering informatics, manufacturing planning, process modeling for engineering applications

1 Introduction

Additive manufacturing (AM) is a rapidly growing industry that is making an impact on global manufacturing sectors such as aerospace, automotive, and medical [1]. In AM, parts are built up using additive, layer-by-layer, fabrication processes, contrasting subtractive manufacturing processes that subtract material from solid objects using a variety of cutting tools. Since the first major patent of "stereolithography" in 1986 by Charles Hull [2], AM has transitioned from rapid prototyping into full commercial production thanks to the advancements made in three-dimensional (3D) printing machines [3,4]. AM encompasses different types of 3D printing technologies, where each technology has its own characteristics and challenges [5]. Powder bed fusion (PBF) is a type of AM technology where thermal energy selectively fuses regions of a powder bed [6]. PBF can be subdivided into two branches: laser-based PBF (LPBF) and electron beam melting (EBM). Although this work focuses on the LPBF technology, which uses a high-power laser to selectively melt geometric patterns into

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Contributed by the Computers and Information Division of ASME for publication in the Journal of Computing and Information Science in Engineering. Manuscript received April 15, 2022; final manuscript received September 9, 2022; published online October 20, 2022. Assoc. Editor: Nicholas Meisel.

layers of metal powder and form a fully dense freeform part [7], the proposed data representations could also be applied to EBM processes. When manufacturing with LPBF, the resulting part quality is established by many process parameters, such as laser power, scan speed, hatch space, and layer thickness [8,9]. LPBF is susceptible to the manifestation of process flaws such as cracks, residual stresses, and pores [10,11]. Therefore, mapping and selecting process parameters are important steps toward regulating thermal distribution, controlling microstructure formation, and maintaining tensile properties of the part during fabrication.

It is well known that digital thread applications for design, manufacturing, inspection, and maintenance favor the utilization of computer-aided modeling and associated data exchange formats [12,13]. However, not all data exchange formats satisfy the requirements for PBF processes. For example, popular data exchange formats, such as Standard Tessellation Language (STL) [14] and Additive Manufacturing File (AMF) [15], describe the surface of a 3D part in the form of a triangle mesh. However, when using approximated geometry formats, large file sizes are exhibited as the geometric complexity of the solid part increases. In addition, STL and AMF lack definitions for process parameters that are needed to drive the fabrication of an additive part. On the other hand, the Standard for Exchange of Product model data (STEP) is a family of ISO 10303 standards that define methods for describing and exchanging product data throughout the lifecycle of a product [12]. STEP standards are represented by application protocols (AP) that describe the purpose and functional capabilities as defined in the standards. For geometry definitions, geometric dimensioning and tolerancing (GD&T), and product manufacturing information (PMI), the STEP standards are described in the ISO 10303-242 managed model-based 3D engineering AP242 [16]. Furthermore, the STEP compliant Numerical Control (STEP-NC) extends the STEP definitions with NC-machining tool characterization and control, work plans, and operations capabilities that are described in the ISO 10303-238 model-based integrated manufacturing AP238 [17]. STEP-NC was developed to answer the smart manufacturing needs of standardization for modern computer numerical control (CNC) machines. STEP-NC allows design data to be encapsulated into the manufacturing process to reduce the loss of information between the design and the manufacturing stages, reflect the geometric properties of the part into the fabrication process, and replace G-code [18] with broader instructions for manufacturing control.

Recently, STEP-NC has been updated with standardized information models for general AM processes, which are documented in the ISO 14649-17 standard [19], or part-17 for short. However, the current version of the part-17 standard does not have definitions for process parameters that enable control of the manufacturing process in PBF technology. To bridge this gap, this paper proposes STEP-NC compliant data representations for PBF. More specifically, the proposed representations enable process control in PBF manufacturing by defining new parameters with operation, technology, and scan strategy capabilities. Figure 1 describes the relationship between the STEP and STEP-NC standards. Here, the geometry definitions, GD&T, and PMI are described in the second edition of AP242 [16], which is extended by the NC-machining, operation, and general AM definitions as described in the second edition of AP238 [17]. The proposed data representations for PBF technology are assumed to be part of the upcoming fourth edition of AP238. With a clear understanding of the different process parameters for each AM technology, it is possible to identify key elements, entities, and attributes that could be used in establishing a system's perspective of the process plan as a whole [20]. In the case of PBF manufacturing, such process parameters are essential enablers of part quality optimization and elimination of fabrication flaws and defects.

The structure of this paper is detailed as follows. Section 2 covers the related work. Section 3 describes the standardized data representations for AM and identifies the current challenges. Section 4 presents the proposed STEP-NC data representations for PBF. Section 5 discusses the approach to model the proposed data representations, as well as the generation and simulation of PBF process plans. Section 6 concludes this paper.

2 Related Work

AM has gained considerable research attention in recent years. With new materials, technologies, and designs for AM, there is a

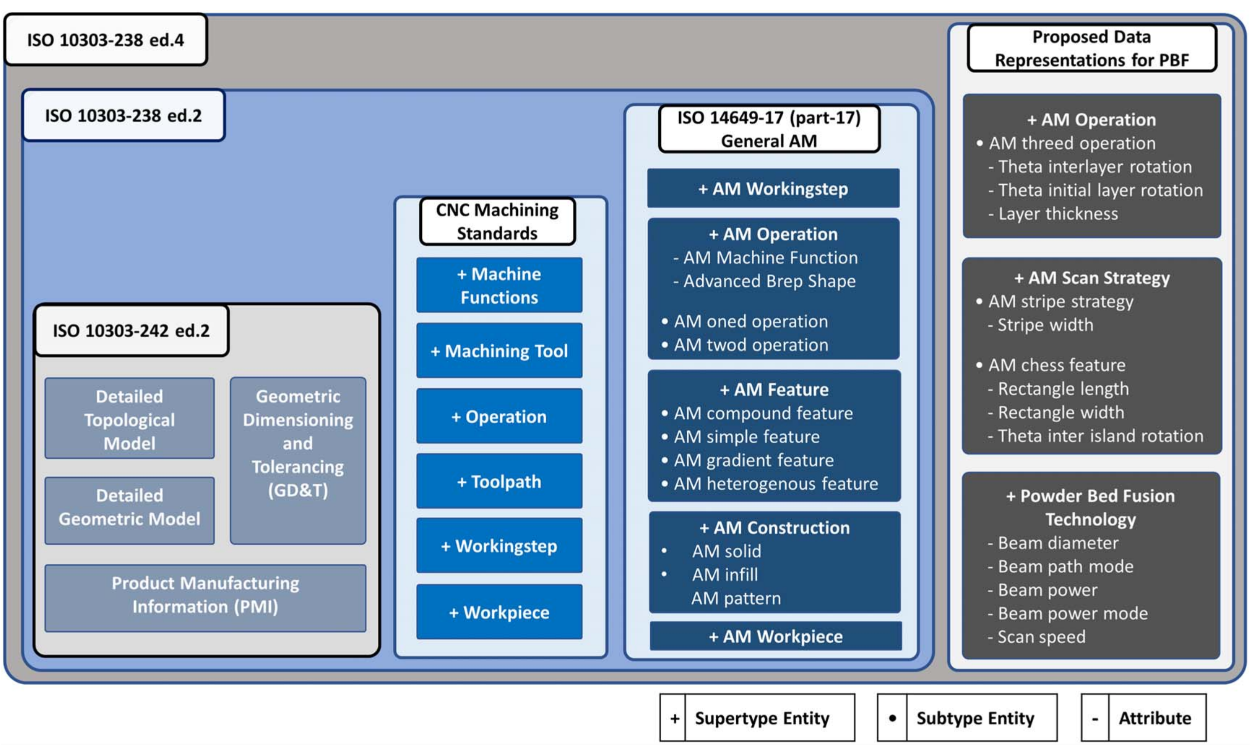

Fig. 1 A diagram that highlights the relationship between the STEP and STEP-NC standards and data representations

need for information models that could describe the design and process parameters of an AM product and contain such data in an exchangeable format. STEP-NC provides an opportunity for developing data models that streamline the flow of information from part design to part manufacturing. In addition, STEP-NC would eliminate the need for data model transformation between different file formats by maintaining the AM product design and process requirements. A selection of recent research efforts that utilized STEP-NC data models for AM applications is discussed next.

For AM application processes, Um et al. [21] proposed a STEP-NC-based representation method for process planning and remanufacturing in AM applications. The proposed method used geometric reasoning to find discrepancies between the original part's STEP-NC file and the defective scanned part to be repaired. The STEP-NC file is then updated with the repair feature and the executable operations, a milling process to remove the defective surface and flatten the part, and a laser cladding process to create the repair feature. Results from a comparative case study showed that STEP-NC data kept the errors low and enabled high-accuracy process planning and tolerance inspection. In the application of 3D slicing, Um et al. [22] proposed a squashing algorithm to process complex sliced layers without missing volumes. To increase the accuracy in the geometry definition process, the authors presented a data representation based on STEP-NC for multimaterial and multidirectional layers in a boundary-representation standard model. The data representation followed the standardized general AM definitions in part-17 [19]. Results from case studies showed that using boundary representation and the squashing algorithm in the geometric process of AM improved the accuracy of the final part when compared to other data representations.

In terms of digital thread architecture, Bonnard et al. [23] proposed a STEP-NC data model for AM technologies and presented a STEP-NC platform on an industrial AM system for data model implementation and validation. The proposed method introduced AM definitions in the CNC-based ISO 14649-1 data model standard [24] by using one ISO 14649-10 general process data model [25] for all manufacturing processes and created specific parts as process data for AM in compliance with the part-17 standard. This enabled machining processes and AM processes to be on the same level of execution, whereas the general process data yielded a single data model that provided multiple manufacturing processes and different process plans for similar part designs. To validate the STEP-NC AM data model, the authors conducted experimental tests of fabricating two test parts, which have been constructed and validated using the proposed digital thread platform.

To demonstrate the flexibility of STEP-NC data models, Rodriguez et al. [26] presented a method that applied STEP-NC programming in AM processes based on the machining data model of AP238 [17]. The proposed methodology consisted of five implementation activities, which handled the slicing of the part model, generating the AM STEP-NC program, building the AM machine kinematic model, simulating toolpath, and fabricating the part. For experimental validation, a test part was fabricated using a RepRap 3D printer, where a G-code program was generated through the post-processor of a STEP-NC machine. Finally, the toolpath information contained in the G-code format file was interpreted by the controller to generate movements on the powered axes of the RepRap printer.

For qualification and inspection, Riaño et al. [27] proposed a STEP-NC-based integrated architecture for closed-loop inspection in AM digital thread. The proposed architecture consisted of an AM linear parallel delta robot, an inspection system using a coordinate measuring machine (CMM), and a quality control system. For this architecture, a STEP-NC digital model was used as the fundamental basis of integration, which contained the solid model and metadata of the design specifications such as GD&T. In a case study, a closed-loop inspection was performed through execution of inspection planning, measurement collection, feature inspection, tolerance operation, and correlation of the system results.

The reviewed literature demonstrated the viability of STEP-NC data models for AM software applications, part fabrication implementations, and digital thread architectures. However, the reviewed approaches mostly focused on AM implementations, where combinations of STEP-NC definitions from part-17 and CNC-based machining definitions were derived to achieve successful part builds. On the other hand, one might explore alternative data model approaches in STEP-NC that link process parameters of AM technologies with their corresponding process controls. Therefore, this paper proposes STEP-NC compliant definitions that provide detailed process planning capabilities for PBF technology in AM, while remaining neutral of AM machine implementations.

3 Standardized Data Representations

This section presents the AM standardization of STEP-NC data representations in two parts. The first part reviews some of the standardized STEP-NC data representations for AM in the part-17 standard that are applicable to PBF processes. The second part identifies several challenges when applying the current standard definitions to PBF processes.

3.1 STEP-NC for Additive Manufacturing. The part-17 standard [19] is a key form of data representations for AM definitions in STEP-NC. The defined data are represented in an object-oriented manner using the EXPRESS language [28]. The data representations are structured in a hierarchy of entities that can be instantiated, attributes that associate a role with an entity, and datatypes that declare the type of value for the assigned entity or attribute. Figure 2 shows a graphical EXPRESS schema (EXPRESS-G) of data representations that are defined in part-17. For instance, the entities that are indicated with the number "1" below them are considered supertype entities, which define a parent-to-child relationship with subtype entities that branch out from them. The part-17 standard, along with other standards described in AP238 [17], enables AM data exchange between computer-aided design (CAD), computer-aided process planning (CAPP), and computer-aided manufacturing (CAM) systems. Essentially, a CAD software enables an engineer to design, modify, and optimize a 3D model of a part. In part-17, the volumetric part model is described as an `AM_workpiece`. Multiple `AM_workpiece`(s) can be concatenated to form a manufacturing hierarchical structure. To fabricate a part, engineers use a CAPP software to generate the program necessary for executing the process plans. The `Executable` entity is an important part of AP238, which commands the execution of processes either sequentially or in parallel. The information associated with the atomic transformation of an AM executed process is included in the `AM_workingstep` entity. The `AM_workingstep` holds descriptions of an `AM_feature`, which is the geometry under fabrication, and an `AM_operation`, which describes the process parameters of the fabrication.

The geometry of an `AM_feature` can be compounded by linking multiple features. Each feature can be defined as either an `AM_simple_feature`, an `AM_gradient_feature`, or an `AM_heterogenous_feature`. As the name suggests, the `AM_simple_feature` defines a simple additive geometry with a skin and a core, such that the skin thickness is assumed to be uniform, and only one color and one material can be selected for a given feature. On the other hand, the `AM_gradient_feature` enables a gradient of colors and materials to be defined inside an `AM_feature`. The `AM_heterogeneous_feature` uses a freeform formula to describe atomic mixtures of multiple materials and colors within the same feature. The `AM_construction` entity enables a feature to be additively constructed as a solid, or as an infill based on the density and direction of predefined patterns such as honeycomb, concentric, and rectilinear.

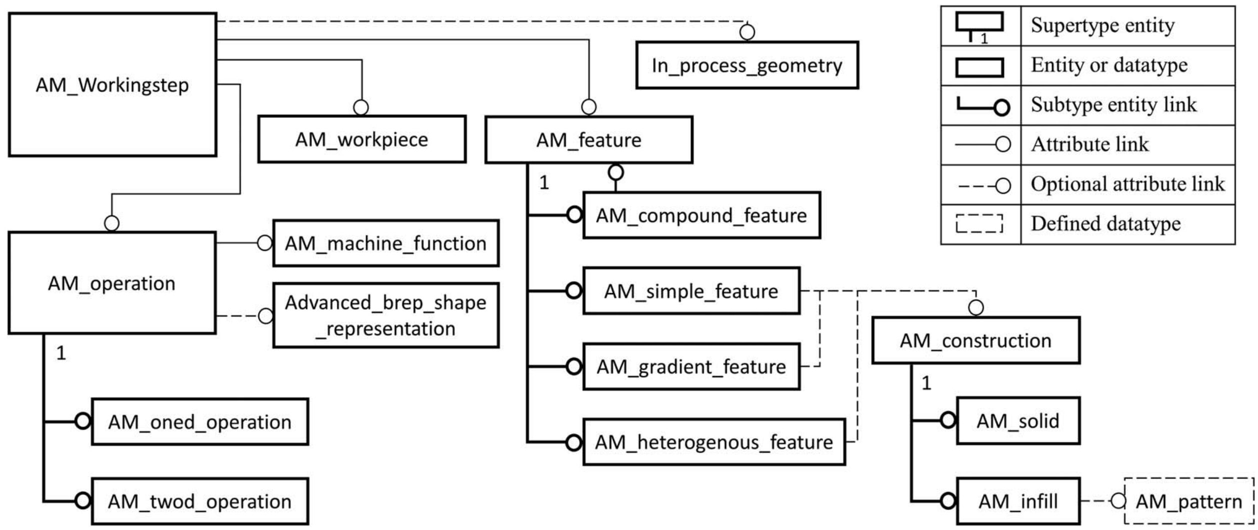

Fig. 2 A diagram representation of the ISO 14649-17 (part-17) standard entities applicable for PBF

The AM_operation entity describes the process parameters attributed to the manufacturing of an additive feature, which are AM_oned_operation and AM_twod_operation. In addition, AM_operation identifies the machine functions and the support structure needed for this operation. Nevertheless, the process parameters of an AM_operation depend on the type of the AM fabrication process. For example, the AM_oned_operation is applicable for one-dimensional (1D) additive deposition processes, where a freeform operation repeats the deposition of one filament of material at a time until the full geometry is obtained. On the other hand, the AM_twod_operation specifies the two-dimensional (2D) operation on the elementary surface geometry of each layer and defines the thickness of a layer based on the normal direction.

3.2 Identified Challenges. The AM data representations that have been included in part-17 do not fully capture the necessary requirements for process control in AM technologies such as PBF. The following discussions identify several challenges and possible ways to overcome them.

One of the main characteristics of the AM_feature entity is the ability to specify the way a feature is constructed by using the AM_construction entity. This is achieved by specifying the direction, the density, and the type of the chosen scan pattern. However, the specifications associated with the scan patterns are not currently defined. For instance, common scan strategies in PBF might contain geometric patches within a pattern, also called islands, which require boundary specifications and a rotation angle for each patch [29,30]. Without specifications, AM process plans might suffer from incompatibility issues that might arise during part fabrication. Thus, there should be a modular definition of scan strategies that reflects the essential characteristics of a pattern and provides the parameters necessary to maintain control of the PBF process.

The attributes of the AM_twod_operation entity identify the geometry, the thickness, and the direction for additively building a feature layer-by-layer. However, AM_twod_operation does not have process parameters for describing the interlayer relationship in a 3D build. Furthermore, laser power, scan speed, hatch space, layer thickness, and scan strategy influence the geometry and density of the resulting part when fabricated using LPBF [30]. Therefore, careful application and control of these process parameters are necessary to ensure the quality of the additive part and reduce the internal defects that might occur during fabrication.

4 Proposed STEP-NC Data Representation Specifications

This section details the proposed STEP-NC compliant data representations for PBF processes. Specifically, the defined data are contained in four STEP-NC compatible entities. These entities are the AM_operation, the AM_threed_operation, the AM_scan_strategy, and the Powder_bed_fusion_technology. In what follows, a detailed discussion of the design and function of each entity is presented.

4.1 Additive Manufacturing Operation. Figure 3 shows the amended AM_operation entity and its subtype entities including the proposed AM_threed_operation. The combined entities provide the processing parameters necessary for additively building the geometry of an AM_feature using PBF. The AM_operation entity includes two existing attributes, machine_functions and its_support_geometry, and three new attributes: hatch_space, its_scan_strategy, and its_technology.

Figure 4 shows the hatch_space attribute that represents the distance between two consecutive laser scan paths. Here, the hatch_space is specified using the millimeter (mm) unit and the length_measure variable, which takes in a real number value. It is important to note that selecting a proper hatch space depends on the settings of other process parameters such as the laser scan speed and the laser spot diameter among others [30]. For CAPP and CAM software applications, this provides flexibility when selecting the type of hatch_space definition, whether being explicitly defined or derived based on other process parameter settings. Furthermore, proper control of the hatch_space ensures the consistency of the melt pool tracks as well as track-wise and layer-wise remelting [31].

The its_scan_strategy attribute provides access to the AM_scan_strategy entity, which contains parameters of scan patterns that are common in PBF processes. Likewise, the its_technology attribute is connected to the AM_technology entity, which contains the Powder_bed_fusion_technology entity that holds the parameters for driving the manufacturing process of the PBF technology. The detailed data definitions of the AM_scan_strategy and the Powder_bed_fusion_technology entities are discussed in the following subsections. The proposed AM_threed_operation entity is designed to provide volumetric, 3D operation capability by specifying the rotation angle of the scan strategy for each layer. This entity

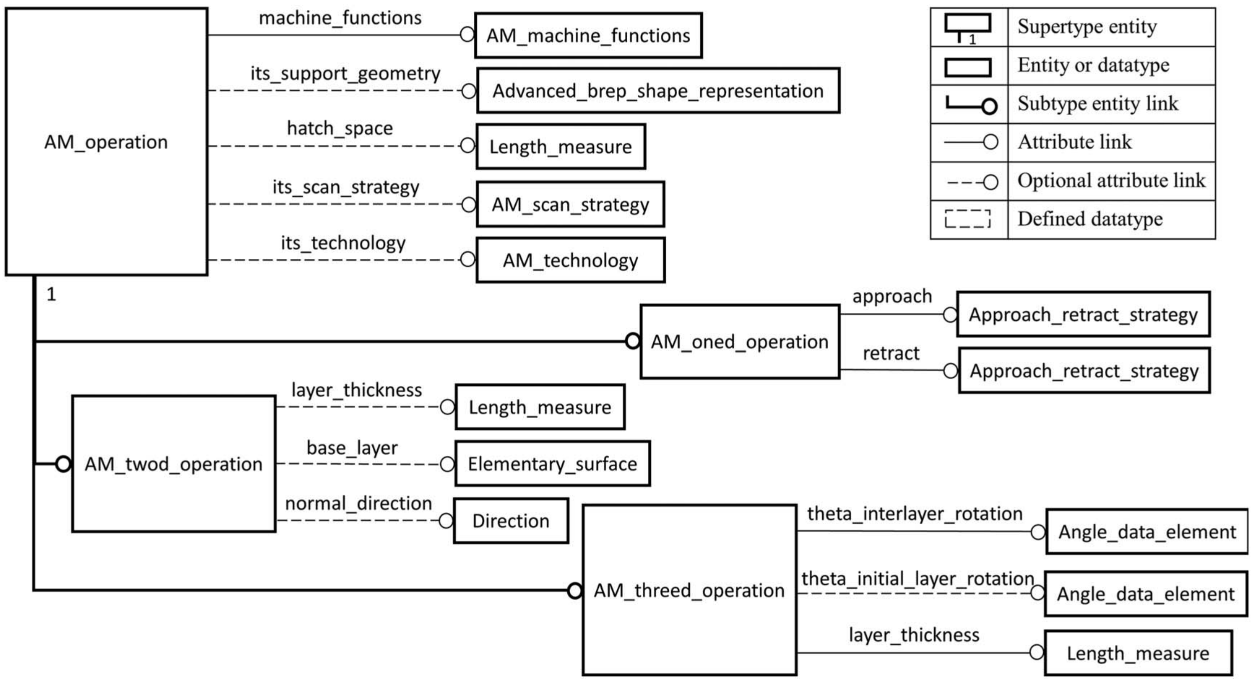

Fig. 3 A diagram representation of the amended "AM_operation" entity and the proposed "AM_threed_operation" entity

defines three attributes: the `theta_interlayer_rotation`, the `theta_initial_layer_rotation`, and the `layer_thickness`.

Figure 5 illustrates the `theta_interlayer_rotation`, which represents the measured rotation angle (θ) in degrees for the scan strategy of the current layer with respect to the scan strategy of the previous layer. Similarly, the `theta_initial_layer_rotation` is the measured angle of rotation in degrees for the first scanned layer of an `AM_feature` relative to the coordinates of the build plate, which serves as the base that the manufactured part builds upon. In PBF, the scan strategies of successive layers are rotated slightly, e.g., 45 deg, 67 deg, or 90 deg, to regulate the thermal distribution over the powder surface, control the microstructure grain size, and growth direction of the powder material, and maintain the desired hardness and tensile strength of the manufactured part [29,32]. The `layer_thickness` is the predefined thickness of a layer, which could be directly inherited from the `AM_twod_operation` or specified according to the geometry of the `AM_feature`. When selecting the thickness of a layer, the powder material properties such as thermal conductivity and density need to be considered as well. This is critical for a successful build because the laser-melted area of the powder, also called melt pool, needs to be large enough to connect the molten tracks in each layer and deep enough to connect to the previous layer [29].

4.2 Additive Manufacturing Scan Strategy. The `AM_scan_strategy` is a parent, or supertype, entity that contains the definitions of two children, or subtype, entities: the

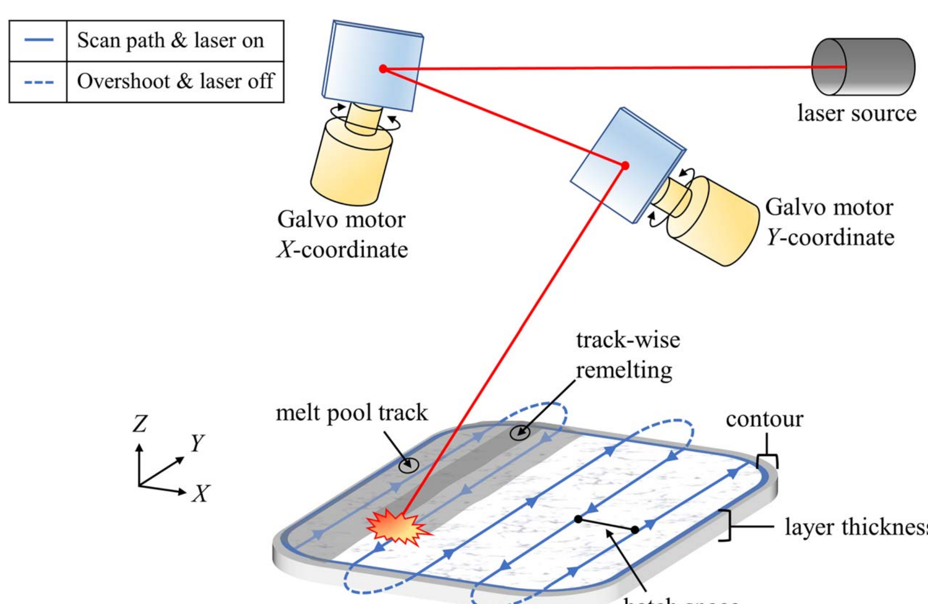

Fig. 4 An illustration of the optical scan controller and process parameters for LPBF

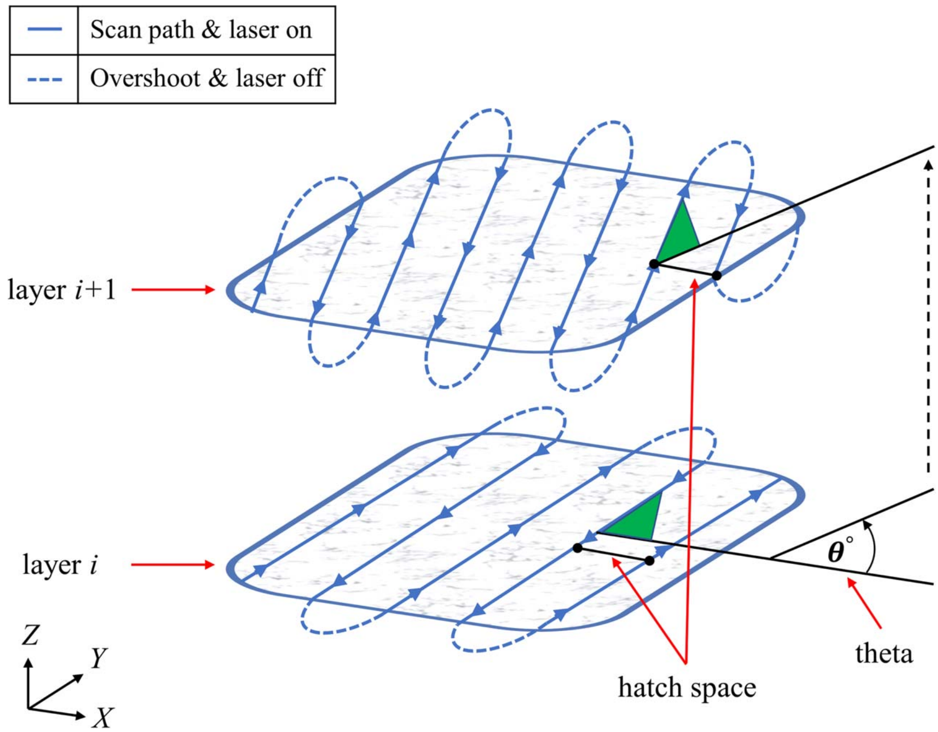

Fig. 5 An illustration of the "theta_interlayer_rotation" of a scan strategy between the layers *i* and *i* + 1, respectively, with the same hatch space

AM_stripe_strategy, and the AM_chess_strategy. Figure 6 shows the diagram of the proposed AM_scan_strategy entity. The AM_stripe_strategy partitions the scan area into segments of stripes. The objective of this scan strategy is to control the thermal gradients for each scanned track by specifying the width of the stripe [33]. The stripe_width attribute is specified using a real number with an mm unit and is contained in the length_measure variable. The AM_chess_strategy, also called an island strategy, is a common scan pattern in PBF manufacturing where the slice of a feature is segmented into rectangular patches akin to a chess board. The length and width of each rectangle are specified as real numbers with mm units using the length_measure variable. In addition, the orientation of each rectangular island can be rotated independently using the theta_inter_island_rotation attribute. In PBF, interlayer rotation plays an important role in balancing the temperature distribution and reducing residual stress [32,34].

4.3 Powder Bed Fusion Technology. Figure 7 shows a diagram of the Powder_bed_fusion_technology entity, which is a subtype entity that is contained in the AM_technology entity, and provides process parameters that are used by an optical scan controller (OSC) system of an LPBF machine [9]. The entity for the PBF technology specifies five attributes: the beam_diameter, the beam_path_mode, the beam_power, the beam_power_mode, and the scan_speed.

The main components of the OSC are the laser beam energy source, the galvanometer motors, and mirrors that control the (X, Y) coordinates of the laser beam movement as shown in Fig. 4. The beam_diameter attribute defines the diameter of

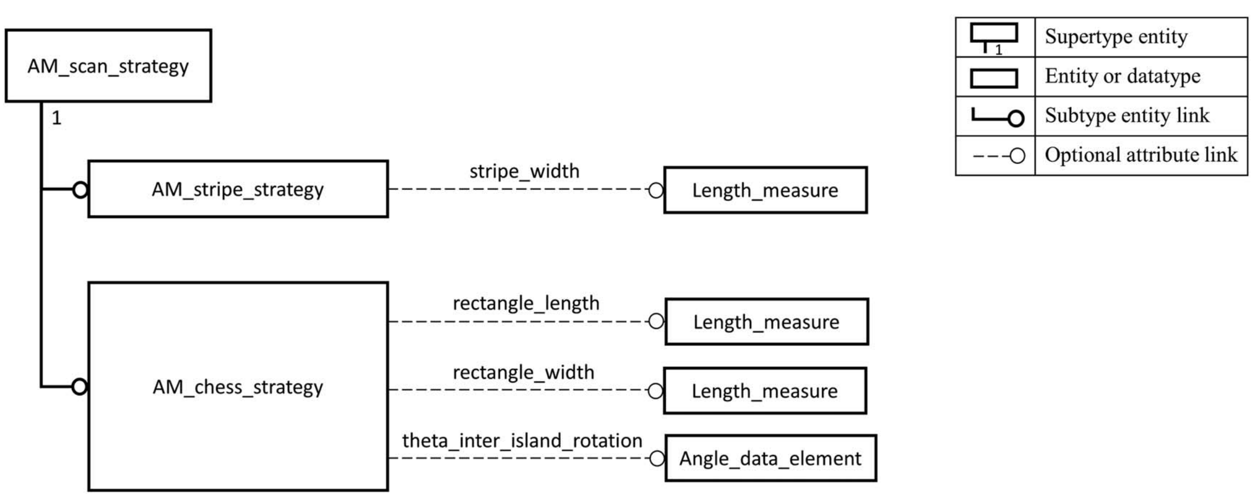

Fig. 6 A diagram of the "AM_scan_strategy" entity and its subtype entities: "AM_stripe_strategy" and "AM_chess_strategy"

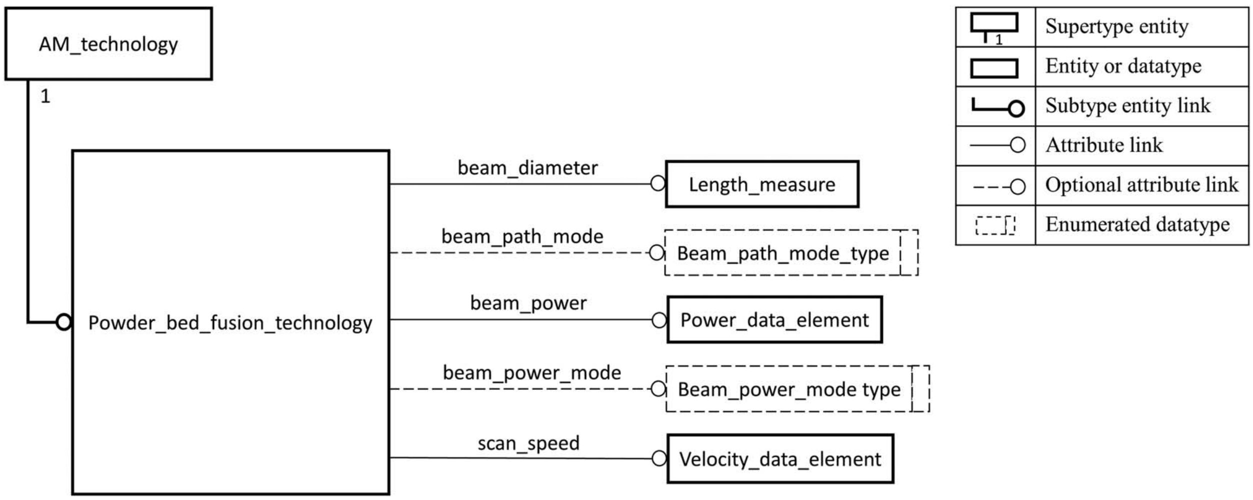

Fig. 7 A diagram of the "Powder_bed_fusion_technology" entity

the laser spot with an mm unit using the `length_measure` variable. The ability to set the diameter of a laser spot could be a factor in increased productivity, such that a larger laser spot would reduce the number of scan lines [35]. The `beam_path_mode` attribute describes how sequential moves are planned, which selects from three path mode types: `exact_stop`, `constant_build_speed`, and `continuous` [9]. The `exact_stop` mode stops the laser motion exactly at the end of each move with maximum allowable deceleration, whereas the `constant_build_speed` mode keeps the motion at a constant speed for the whole move while the laser is on [7]. On the other hand, the `continuous` mode matches the ending velocity of the scan with the beginning velocity of the subsequent scan [9]. The `beam_power` attribute specifies the energy output of the laser unit in Watts and is represented by the `power_data_element` variable. The `beam_power_mode` attribute selects from three power mode types: `constant_power`, `constant_power_density`, and `thermal_adjusted_power`. The `constant_power` mode keeps the laser power constant, and the `constant_power_density` mode holds the power-to-speed ratio constant, whereas the `thermal_adjusted_power` mode compensates for the local variation of thermal property by changing the laser power [9]. The `scan_speed` attribute represents the rate at which the laser beam moves over the designated scan path. The `scan_speed` is measured in millimeter per second (mm/s) and is specified using a real number value. The speed of the laser scan movement could be explicitly specified to represent the maximum scan speed along the scan path. On the other hand, the selection of a `beam_path_mode` would allow for some variability in the scan speed (e.g., when selecting the `exact_stop` mode, the scan speed will decrease to zero at the end of each move). Nevertheless, regulating the scan speed of a laser plays a key role in combating various microstructure and materials-related issues such as micro-segregation, undesired texture, and columnar grains [8].

5 Modeling and Simulation

This section discusses the steps taken to model and simulate the proposed STEP-NC data representations for PBF in AM. Modeling the proposed data representations is influenced by the Additive Manufacturing Metrology Testbed (AMMT) of the National Institute of Standards and Technology (NIST) [36]. The AMMT is an LPBF testbed with a custom controller and various metrology instruments such as an in-line imaging camera and a staring high-speed camera, which are used to collect in-situ monitoring data [9]. For the proposed data representations, a mapping strategy was developed to map the process planning and manufacturing parameters of the AMMT to their corresponding entities in the part-17 standard, and identify gaps in data definitions that the proposed data representations will fill in for PBF manufacturing. The development stages of the mapping strategy are explained below, followed by the simulation of STEP-NC generated LPBF process plans, and then the challenges observed while accomplishing these tasks.

5.1 Mapping Data Representations. The first stage of the data mapping strategy is a comprehensive system analysis of the AMMT software to understand the utility and behavior of the system. The process planning and the manufacturing command controls of the AMMT are driven by the Simple Additive Manufacturing (SAM) utility, which provides a reference architecture for an open platform AM control software [7,9]. The SAM utility uses a 3D CAD model and user-specified inputs to generate an AM G-code file [9], which is a modified version of the RS-274 standard [37]. The AM G-code file describes the (X, Y, Z) coordinates of the scan path and specifies the laser power with the command letter "L" and the laser diameter with the command letter "D" for each layer. Then, an interpreter module converts the AM G-code file into time-stepped commands, enabling the AMMT controller to operate the power outputs of the laser unit and the (X, Y) coordinates of the galvanometer motors. The time-stepped commands are based on the XY2-100 protocol [38], where each command line is executed by the AM controller every 10 μs [9]. The comprehensive analysis of the AMMT system provided important information regarding the utilization of data elements and the executions of layer-by-layer building commands.

The second stage is a gap analysis that identifies crucial process parameters in the AMMT system that was not defined in the current part-17 standard. When examining the path planning step in the SAM utility, the programming procedure is contingent on user inputs that specify the process parameters of each layer, such as the layer thickness and the rotation angle of the scan path. In addition, the user specifies the type of scan strategy and the hatch space that separates each path. However, the SAM process parameters related to the laser power, the laser power mode, and the scan speed are dependent on prior knowledge of the material properties of the powder metal, and the technological capabilities of the AMMT OSC system. Therefore, the proposed data representations encapsulate the necessary path planning parameters in a modified `AM_operation` entity, where the defined process parameters of additive layers are succinctly linked in a uniform, STEP-NC data format.

5.2 Process Plan Simulation. This part discusses the approach for validating the proposed data representations by generating process plans and evaluating them in a simulated

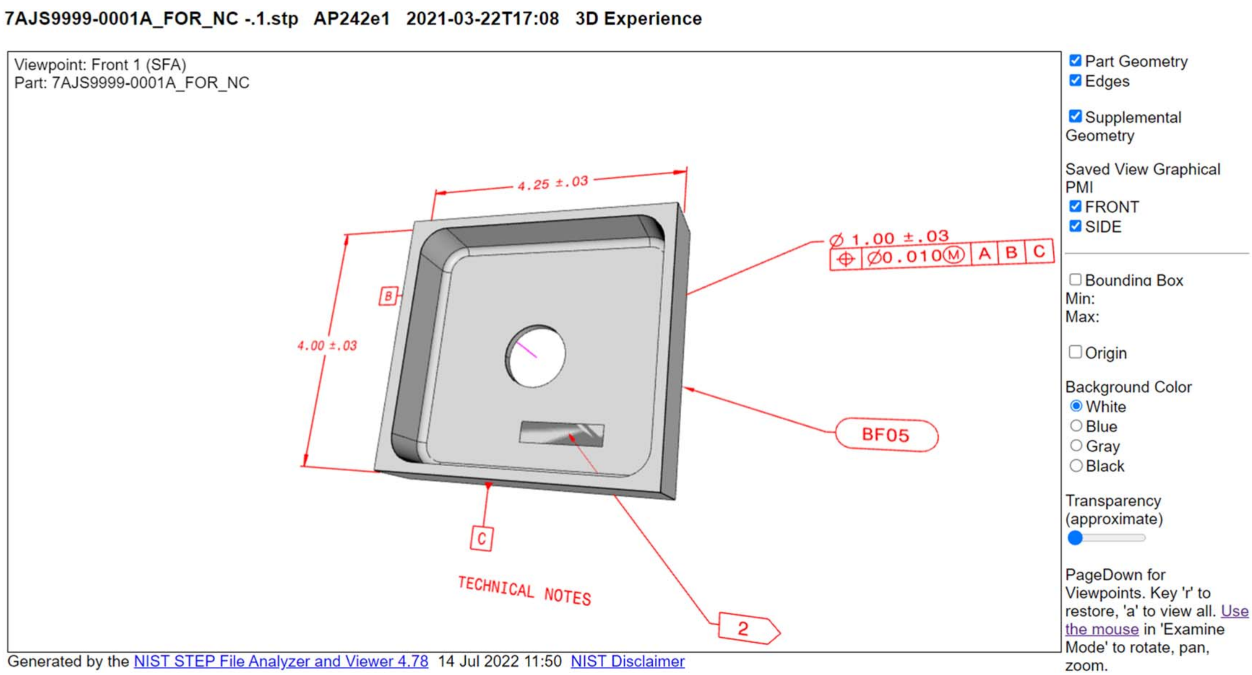

Fig. 8 A 3D model of the test part as shown in the NIST STEP File Analyzer and Viewer [39]

environment. First, a 3D CAD model of a test part was created in a STEP file format. Figure 8 displays the 3D model of the test part using the NIST STEP File Analyzer (SFA) software [39]. Table 1 details the geometry dimensions of the 3D model and the process parameters used in generating the process plans. Next, the STEP Tools software[2] was used to slice the 3D model, apply a scan strategy on each layer, and specify the LPBF technology parameters for each scan path. The result from this step is a process plan that is generated in a STEP-NC format. To evaluate the generated process plan, a PYTHON script was developed to convert the STEP-NC file into an AM G-code file, which could then be read and simulated using the NIST SAM utility [9]. Figure 9 demonstrates the outlined steps from selecting a 3D model to process plan generation and simulation, along with excerpts from each data file.

To showcase the capabilities of the proposed data representations, two process plans were simulated using the NIST SAM utility. Both process plans used the `constant_power_density` as the `beam_power_mode_type`, but with different `beam_path_mode_type`(s). Here, the SAM utility acts as a CAM software that interprets the AM G-code messages, which have been converted from STEP-NC format, then encodes time-stepped commands and calibrates them to the OSC technology settings of the NIST AMMT. Figure 10 shows a sliced layer of the 3D model for the first process plan, with the `constant_build_speed` as the selected `beam_path_mode_type` and the colored laser power gradient. To maintain a constant build speed, the laser scan paths are extended beyond the boundary of the sliced geometry. This is to allow the laser to accelerate while the laser is switched off, and starts the scanning process with the laser on once the required `scan_speed` value is reached. After finishing the scan path, the laser is switched off and the OSC decelerates during the overshoot pass, then returns to accelerate for the next scan path. Figure 11 shows a sliced layer for the second process plan, where the `beam_path_mode_type` was chosen to be the `exact_stop`. Here, the laser `scan_speed` values adapt to the laser position on the scan path, such that the laser starts to accelerate at the beginning of the scan path, maintains the set `scan_speed`, then decelerates until stopping exactly at the end of the scan path and repeats the process for the next scan.

[2]https://www.steptools.com/

Table 1 Units of measurement for the process parameters of the 3D model

Process parameters	Units of measurement
3D model dimensions (*X*, *Y*, *Z*)	(42.5, 40, 10) mm
Hatch space	0.1 mm
Beam power	285 W
Beam diameter	0.085 mm
Layer thickness	0.04 mm
Scan speed	1000 mm/s
Theta interlayer rotation	67 deg
Theta initial layer rotation	0 deg
Theta inter island rotation	90 deg

Note that the laser `beam_power` values are also adapted to the laser position and the variations in the `scan_speed` values because the `constant_power_density` holds the `beam_power` to `scan_speed` ratio constant.

The generated process plans and their scan path simulations serve as examples for the capabilities of the proposed data representations in PBF manufacturing. Of course, other CAM software could interpret the process plans in different ways that match the settings of an AM machine. Nevertheless, the proposed data representations highlight the potential for STEP-NC data models that conform to the AM technology and give CAM software the freedom to interpret the data models and choose the implementations that are appropriate to the AM machines.

5.3 Challenges and Observations. Following the development of the mapping strategy and the simulation of process plans, several challenges have been realized. In AM, the relationship between process parameters and geometry parameters is not necessarily clear and needs to be well understood. For instance, specifying the hatch space value depends on the settings of other parameters, such as the laser beam power and diameter, which are technology parameters, the layer thickness, which is a process parameter, and the width of a stripe, which is a scan strategy parameter. Such an observation kept recurring throughout the development of the data mapping effort. One explanation is that the process control in PBF impacts the structure of a part at the micro-

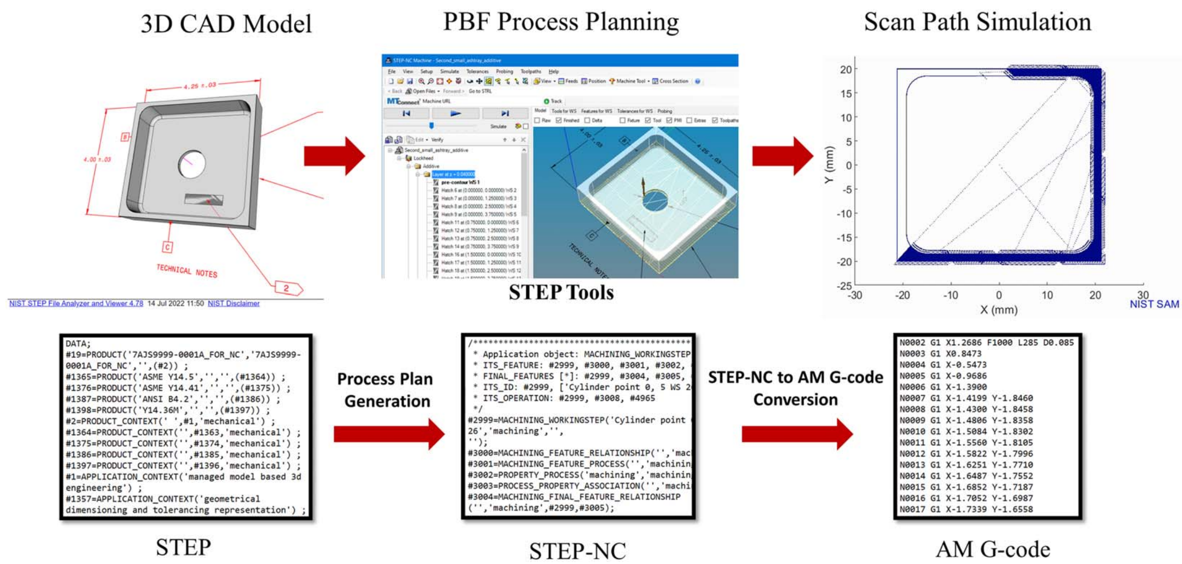

Fig. 9 Steps for PBF process plan generation and scan path simulation, and the data files shown below each step

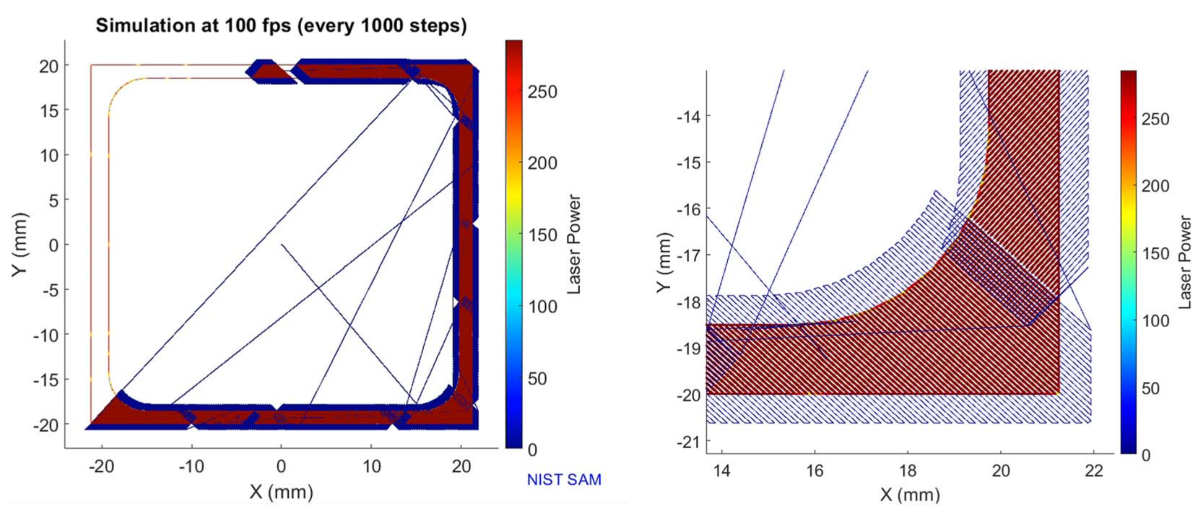

Fig. 10 Simulation of the generated process plans (left) at 100 frames per second (fps) using the "constant_build_-speed" mode and the "constant_power_mode", and a closer look at the simulated scan paths (right), along with the laser power gradient

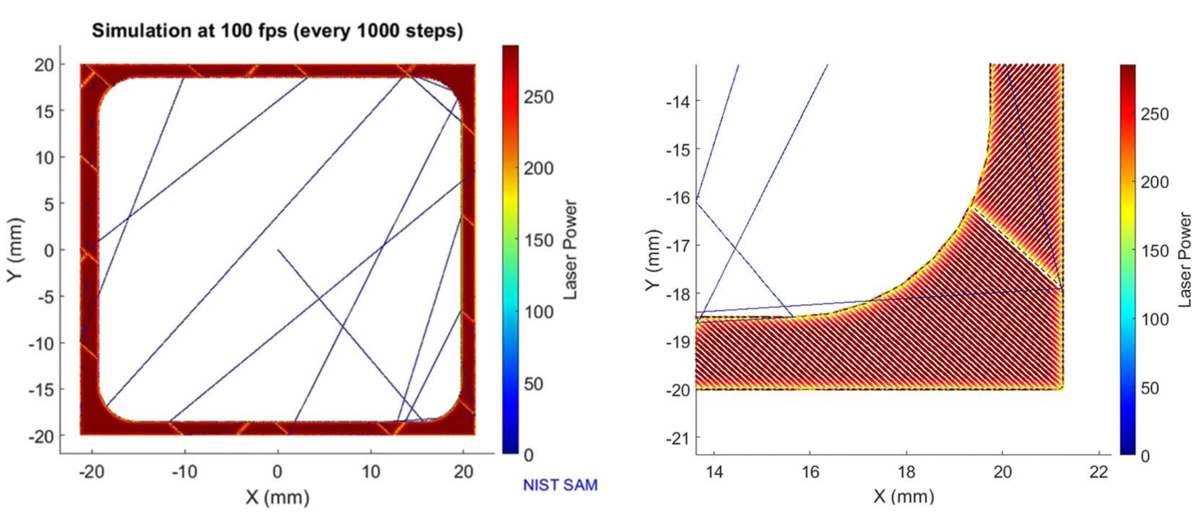

Fig. 11 Simulation of the generated process plans (left) at 100 frames per second (fps) with the "exact_stop" mode and the "constant_power_mode", the simulated scan paths (right), and the laser power gradient

scale, meso-scale, and macro-scale [40]. Therefore, the assigned parameters, whether from geometry or process, rely on compounded parametric relationships that are designed to control the microstructure formation and the tensile properties of the final part. Another challenge is faced when considering the terminology related to the defined parameter. For example, when reviewing the AM literature, many interchangeable terminologies are observed, such as the terms scan pattern and scan strategy [8,9]. However, there are ongoing efforts to define and standardize more terminologies that would simplify communications between members of the AM community worldwide [6]. Likewise, when designing data representations for a STEP-NC compliant entity, many combinations of attributes and datatypes could be formulated to achieve similar definitions or equivalent processes. In addition, the declaration of a parameter might occur at the global level of a supertype entity, such as `AM_operation`, or at the local level of a subtype entity, such as `AM_three_operation`. Proper selection of the declaration scope of a parameter could mean the difference between a globally available definition and a custom-built one. Therefore, defining a parameter or representing a data element should encompass not only the syntax of the definition but also the semantics that reflect its purpose and function.

6 Conclusion

This paper presented STEP-NC compliant, AM data representations for LPBF. The proposed AM data representations encapsulated process parameters of LPBF in a hierarchal structure using the `AM_operation` entity. Furthermore, the parameters associated with the PBF technology and AM scan strategies, respectively, are defined. Simulation results demonstrated the applicability of the proposed data representations for granular control of process parameters in PBF manufacturing.

For future work, an investigation into the modeling, process planning, and fabrication of a real LPBF part using the proposed STEP-NC data representations will be attempted. The implementation of this approach is critical for examining the compatibility and functionality of the defined parameters in a real-world, AM build scenario. In addition, the findings of this approach are expected to broaden the scope of information representation and the mapping of more parameters and definitions across different segments of the AM data spectrum.

Disclaimer

Certain commercial systems are identified in this paper. Such identification does not imply recommendation or endorsement by NIST; nor does it imply that the products identified are necessarily the best available for the purpose. Furthermore, any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NIST or any other supporting U.S. government or corporate organizations.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

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