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Model-Based Production Operational Control for Metal Additive Manufacturing

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Abstract

Metal additive manufacturing processes are influenced by many variables that affect the produced material to varying degrees. This wide range of variables and the complex fusion mechanisms inherent to these processes often result in a manufacturing process with poor repeatability and reproducibility. This is a qualification and certification concern for critical industries. This research aims to investigate the application of manufacturing reference architectures and models for metal additive manufacturing production definition and control. Such models aid qualification activities by defining information that is critical to quality and controlling production operations. A systems engineering methodology is utilized to design and develop a reference model for metal additive manufacturing operations. A case study is performed to demonstrate how the developed reference model can be leveraged to define requirements, define operations in accordance with the STEP AP238 standard for numerical control, and generate machine-readable process control files. This demonstration illustrates how critical to quality data is captured and managed within the system model for compliance purposes. The proposed reference model provides an architecture for developing and implementing operational digital twins.

Introduction

Control of the metal additive manufacturing (AM) process is important if qualification and subsequent certifications are to be achieved. Production control can be defined as the collection of functions that manage all production within a site or area [1]. Process control is defined as the control of variables that affect the quality of process outputs [2]. Operational and quality control also fall within the production control umbrella. Operational control can be defined as the translation of production plans into the execution of production operations [3]. Production controls aim to control either of three main production aspects, namely, quality, time, and resource or material consumption. The American National Standards Institute (ANSI) and America Makes Standardization Roadmap for Additive Manufacturing (Version 3.0) identify AM process control as an area that lacks standardization and that requires further research and development [2]. Controls for AM and advanced manufacturing are highlighted as a key strategy in the National

Strategy for Advanced Manufacturing and are seen as a driving factor for manufacturing digital twins [4].

Modern metal AM machines and their associated systems and facilities can be classified as smart and advanced manufacturing systems. These systems, and most advanced manufacturing systems, are complex and dynamic, which are by their very nature challenging to control as they can experience a host of both internal and external disturbances [5]. Smart manufacturing and production systems in general attempt to improve manufacturing capabilities through the effective implementation and utilization of digital systems and information [6]. Recently standards have been developed for defining and modeling such smart and digitalized production systems. The Digital Factory framework, formalized in the IEC 62832 series of standards, is a framework that aims to establish a foundation for smart manufacturing by achieving semantic interoperability between elements of smart manufacturing system of systems [4]. This framework defines the production system as a "digital factory" which contains various assets. The characteristics, roles, and relationships of these assets are modeled to form a digital representation, or digital twin, of the production system [7]. The ISO 23247 series of standards details a digital twin framework for manufacturing and is generic for the types of manufacturing operations. This framework defines eight types of observable manufacturing elements (OMEs), which include personnel, equipment, material, process, facility, environment, product, and supporting document [8]. Each of these types of OMEs has certain attributes, and these then can be twinned digitally to provide value to the organization and its operations [8].

During the design and development of smart and advanced production systems, reference architectures and models can be leveraged to improve standardization and reduce errors including the IEC 62264 series of standards (formerly and better known as ISA-95), the ISO 10303 series of standards (referred to as STEP), RAMI4.0, and others [1], [9], [10]. ISA-95 focuses on the interaction between enterprise and control systems, specifically for manufacturing operations. This series of standards provides an ontology and reference model with associated data attributes for manufacturing operations. Three fundamental types of manufacturing control are defined, namely, batch, continuous, and discrete [1]. Metal AM is classified as a discrete manufacturing process as the products produced by this process are treated as discrete and traceable outputs. Metal powder production and processing, on the other hand, is classified as batch processing which is addressed in the ISA-88 series of standards [11].

Model-based production and operational control for AM production have been scarcely researched, although model-based definitions of traditional manufacturing operations do exist in the literature. Model-based definitions of production provides various benefits including information reuse, stakeholder communication, improved configuration and change management, and it can facilitate automation. Eyers [5] reviewed manufacturing control architectures and evaluated these architectures for industrial AM systems. Eyers [5] noted that today's AM-centric production systems still rely on humans as the authoritative control system. Sprock and McGinnis [12] proposed a conceptual model for smart manufacturing operational control. They note that there is a gap between system models, analysis methods, and implementation tools in terms of manufacturing and operational control. Gibbons and van der Merwe [13] investigated the application of a model-based systems engineering (MBSE) approach to designing and developing an AM powder reuse production operation. Interfaces between the equipment and the human operator, activities, and production plan were modeled. This model was then used to demonstrate how production controls and requirements traceability can be achieved. An Air Force Research Laboratory (AFRL) research project resulted in the creation of a digital library of key characteristics and production capabilities for different manufacturing processes and their associated production system resources [14]. These definitions were modeled in SysML and aimed at supporting automated process planning and manufacturability assessments specifically for designers. The research presented in this paper aims to investigate the application of manufacturing reference architectures and models for metal AM production definition and operational control.

Methodology

An MBSE approach is taken in this research to model metal AM production aspects. The ISA-95 reference models are leveraged and instantiated for a specific metal AM production scenario and use case to demonstrate the value of such information models. The ISA-95 models were chosen as they are generic to a broad range of manufacturing applications which allows for the extension and instantiation of these model for both AM and additional advanced manufacturing systems. Figure 1 presents the proposed framework for model-based AM production definition and control. ISA-95 is leveraged for the higher-level production models to architect and orchestrate the manufacturing work cell. STEP-NC, AP238, is leveraged for the lower-level machine-specific process controls, specifically numerical control for the PBF process. ISA-95 provides benefit in terms of definition whereas STEP-NC provides benefit in terms of machine-readable toolpaths and controls. AM process specifications such as ISO/ASTM 52904 define requirements for AM production controls that should form part of the overall information architecture [15]. Both ISA-95 and STEP-NC are manufacturing domain-specific models, although they address different levels of the production system. The framework presented in Figure 1 focuses on the integration between these levels for metal AM control. ISA-95 was leveraged for structuring the model and information, STEP-NC was leveraged for specifying AM specific controls, and SysML was used as the modelling language.

The focus of this paper is on the lower level of the AM production system, Level 2 process and supervisory control and below, as well as the integration between Level 3 manufacturing operations and control and the lower levels as defined in Figure 1. A production line is defined as a series of equipment dedicated to a specific number of products or product families, and a work cell is defined as dissimilar machines grouped to produce a family of parts having similar manufacturing requirements [1]. Work cells typically perform one primary function and can be classified as a unit manufacturing process (UMP), whereby material is transformed in some manner. The environment consisting of a metal laser powder bed fusion (LPBF) machine, the operator, and its auxiliary equipment such as a wet separator, inert gas system, etc. is a type of work cell.

SysML is predominately a systems architectural modeling language. Its primary intent is to define the system architecture, boundaries, and key parameters. SysML is an MBSE modeling language and is beneficial for enhancing stakeholder communication, reducing development risks, improving system quality, and enhancing knowledge transfer, amongst other benefits [16]. Other domain languages and tools are often better suited for modeling specific systems operations. SysML was developed based on the unified modeling language (UML) and still contains many similarities with this language. These languages are object-orientated modeling languages[1]. ISA-95 defines architectural models modeled in the UML language whereby elements of the production system are defined using classes and packages. SysML uses blocks which are a stereotype of the UML class. Similarly, for this research, SysML has been extended to incorporate the rules defined by the ISA-95 standards to create a manufacturing-specific profile, also referred to as a domain-specific language (DSL).

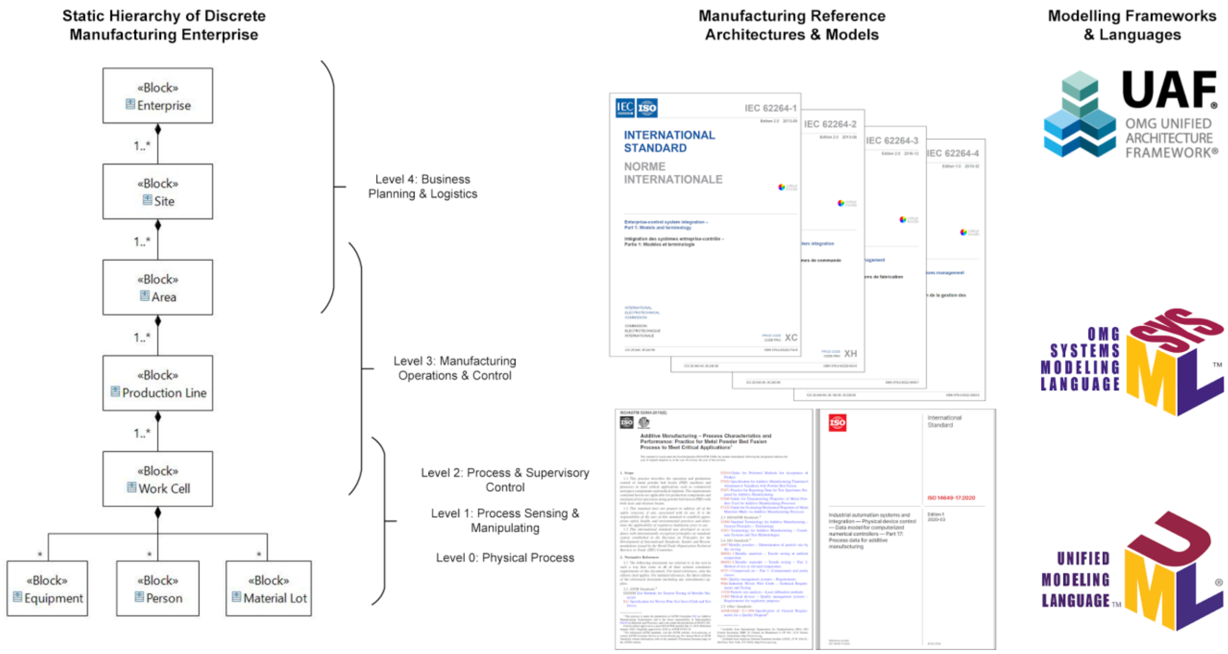

Figure 1: Conceptual framework for model-based AM production definition and control[2].

It is important to note that the term ***equipment*** is used to refer to the roles of various manufacturing resources such as machines, tools, software, facilities, etc. [1]. A process is the dynamic interaction of these production elements. Processes can be generic or specific, independent or dependent of a product, have a workflow, and also have associated parameters. Elements of the production system can be defined to varying levels of detail. Generic models can be defined for AM machines, these can be further specified for LPBF machines, and further as a specific serial number of LPBF machines which can be tracked as physical assets within the enterprise. Models can also be created containing actual production information as opposed to planned or defined information. ISA-95 classifies information into three main areas [1]:

1. Production capability information – Availability of people, equipment, and materials.
2. Product definition information – Information such as scheduling, material information, production rules, and plans that define how to make a product.

[1] STEP-NC is modeled in the EXPRESS language which is also an object-orientated modeling language.

[2] Note that equipment and personnel can be located at higher levels of the manufacturing enterprise hierarchy.

3. Production information – Production results including traveler information, inventories, and the execution of schedules.

ISA-95 uses specific terminology for defining different types of activities. The term ***operation*** is used for modeling operations definitions and their associated segments. Production, maintenance, quality test, and inventory are types of operations. When such operations are associated with a specific product, the terms ***product definition*** and ***product segment*** are used. The segments of operation depend on ***process segments*** which are essentially process templates that define classes of resources and information required for said process. A ***work definition*** and its associated types define workflows in addition and are associated with job orders. A ***work definition*** may have a reference to an ***operations definition***. The ***operations definition*** model was expanded for this research to include a ***design specification*** that can form part of an ***operations segment***. This is important for AM production as often aspects of the product and build design drive specific manufacturing and process operations. This expansion allows for the direct association and traceability between design and manufacturing characteristics. The architecture for the ***product definition*** and ***operations definition*** models are the same. In this research, the ***operations definition*** model is used and no differentiation in terminology is used between product-dependent and independent operations. When a ***design specification*** is modeled, this assumes a product-dependent operation. Figure 2 presents the ***operations definition*** model with the proposed extension for the design specification. Only the ***operations segment*** is developed for this research and its blocks are colour-coded for traceability within the case study.

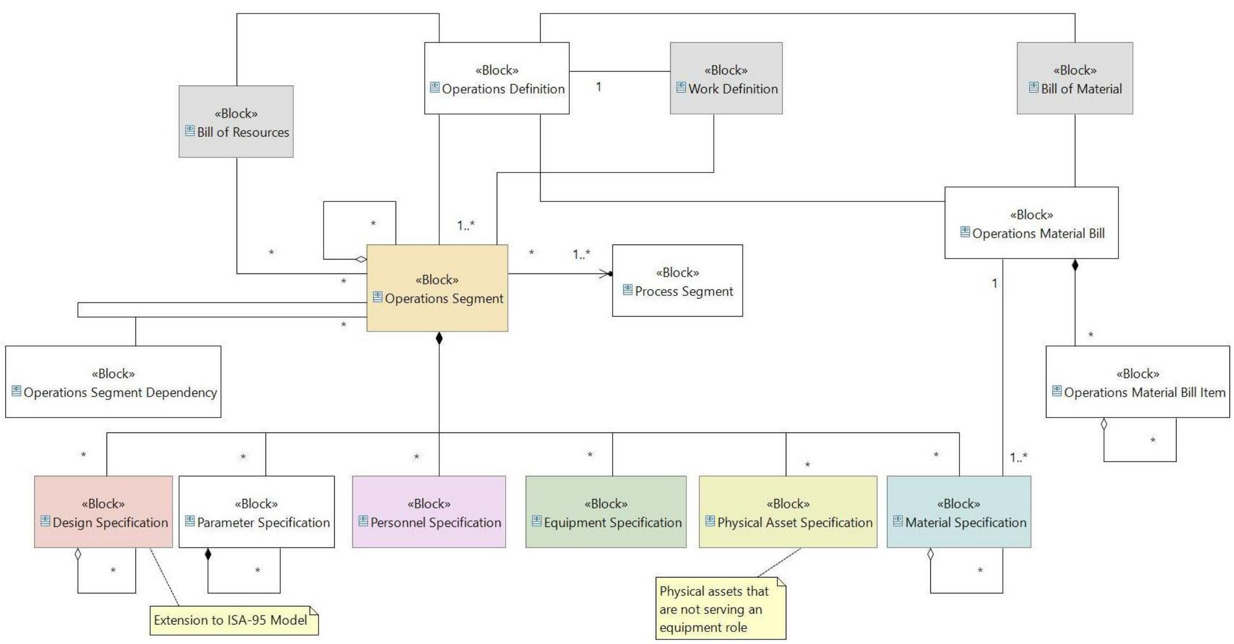

Figure 2: ISA-95 Operations Segment and Extension.

The ***parameter specification*** defines key parameters that can be changed for each operation. At a low level, these parameters drive process control. The attributes of the other specifications are used to define production controls and to define specific production configurations. Such ***operations definitions*** can be created for the different levels of control, see Figure 1, within the production system. It is important to note that not all relationships are defined in these models. There are many dependencies and associations between the different manufacturing elements, i.e. the build plate is dependent on the size of the build platform and chamber in the LPBF machine, but also the type of feedstock that is used. These models are purely for information definition to drive controls. Ultimately, the granularity to which an organization wants or is required to define such control through operations definitions is dependent on the industry they operate within and the types of products they produce.

A reference architectural model is created for metal LPBF production operational control. This model defines the integration between the ISA-95 and AM STEP-NC reference architectures [1], [9], [17]. Requirements defined in ISO/ASTM 52904 for critical AM applications are incorporated into the reference architecture [15]. This architectural model is modeled using the Papyrus 2023-12 modeling tool in SysML and leverages UML techniques [18]. A case study is performed to demonstrate how the proposed architectural model can be used to control metal AM production. The case study focuses on the production of a simple geometry. The architectural models are then instantiated for this production case with specific production parameters and a production system configuration. This instantiated system definition is finally used to populate a STEP-NC-compliant digital manufacturing plan and a machine-readable build file for an LPBF machine in the common layer interface (CLI) format. The STEP Tools Powder Bed Fusion CLI Generation tool was used to generate the CLI file [19].

Reference Architecture for AM Operational Control

Metal AM production operations are performed by Level 2 work cells which are typically scheduled and controlled by Level 3 functions. These Level 3 functions are executed by systems such as manufacturing execution systems (MES). Figure 3 presents a reference operational architecture for metal AM operations. This model defines the types of ***operations segments*** that can be performed by the AM work cell. The operational control architecture shall form the authoritative model for production and shall orchestrate production operations. Where needed, this model can integrate with specific software to transmit control information to specific systems. ***AM operation***s shall conform to the requirements defined in a relevant process specification, such as ISO/ASTM 52904 for critical applications [15]. An ***AM Operation*** shall consist of at least one of each of the ***operations segments*** defined in Figure 3. The exceptions are the ***LPBF Operation*** and the ***Contour Operation***. This allows for ***AM Operations*** that are not LPBF-type operations, such as DED or powder-sieving operations. Although ***Contour Operations*** are typically performed, there are cases where an engineer may want to omit such operations and only perform ***Hatch Operations***. This model is developed for reference purposes and in its current form is agnostic of any design. When instantiated for a specific production instance and product, a ***design specification***, per Figure 2, can be associated with any of these ***operations segments*** to make the connection between the design and manufacturing domains. The ***operations segment dependency*** as seen in Figure 2 is associated with each ***operations segment*** and allows the user to define a sequence of operations and incorporate process logic into their production operations. This dependency element allows for temporal aspects such as time delays, either before or after an ***Operations Segment***, to also be specified.

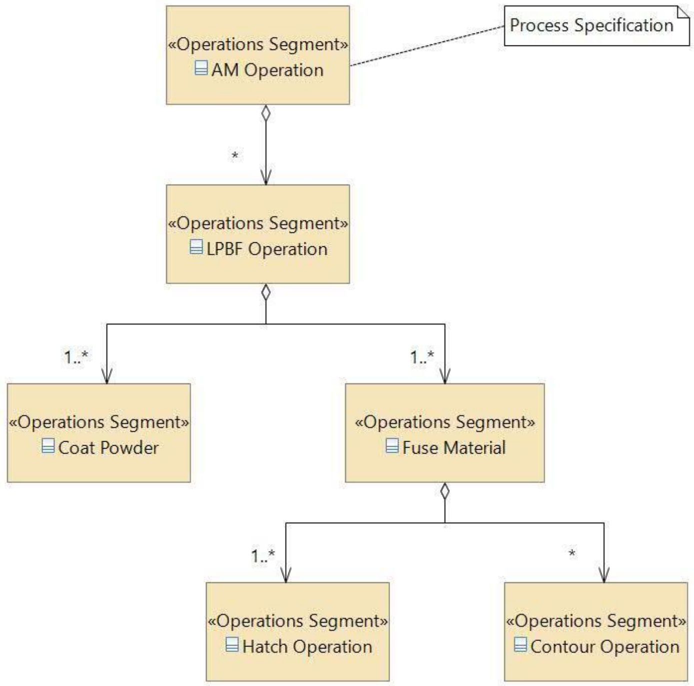

Figure 3: Types of ***AM Operations Segments***.

The ***AM Operation*** model links the high-level work cell parameters with the work cell equipment and an operator. Figure 4 presents the ***AM Operation*** reference model. For compliance purposes, it is best practice to have one operator associated with an ***AM Operation***. This model defines the basic attributes that should be controlled at a high level, although can be built out for specific applications. An ***AM Operation*** can be defined for an operator with one or more ***Qualifications*** or ***Experiences***, and for a work cell with one or more ***Safety Controls***, ***Gas Type***, or ***Alloy Designations***.

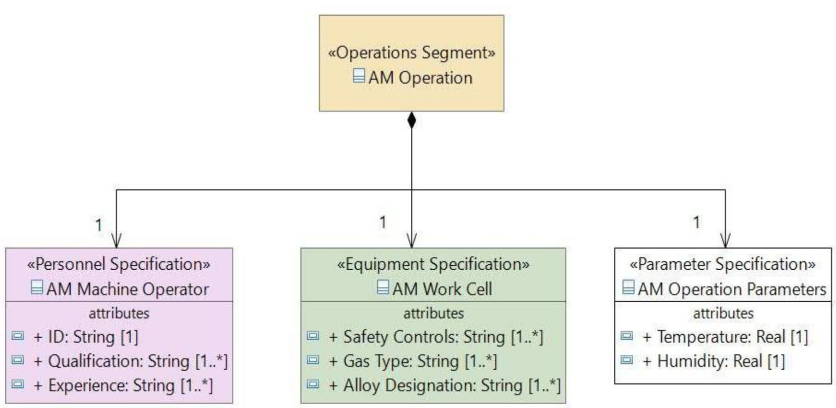

Figure 4: ***AM Operation*** Model.

Production scheduling should be performed for ***AM Operations***. This ***operations segment*** provides the connection between the production line-level and part-specific production controls and the work cell-level operational controls. The higher-level production controls and scheduling functionality define the sequence of work cell operations, such as ***AM Operations*** or ***Heat Treatment Operations***, and the timing of their execution for the full production process.

Figure 5 presents the ***LPBF Operation*** model. One ***Powder Feedstock*** specification is associated with an ***LPBF Operation***, although an operation can be associated with one or more ***Build Definitions***. At this level of an ***AM Work Cell***, other auxiliary operations may be defined for other AM equipment that may utilize other materials or materials in a different condition such as a powder sieving system. This model associates one ***material specification*** with one ***LPBF Operation*** to ensure material traceability. The ***LPBF Operation*** makes the association between the ***Build Definition***, an ***LPBF Machine***, and a ***Build Plate*** on which the parts are to be formed.

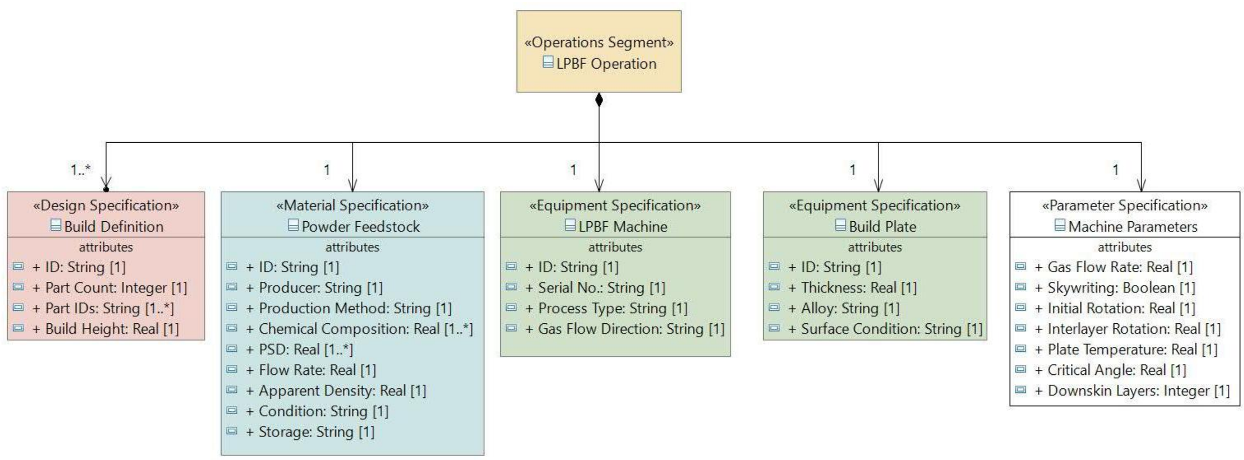

Figure 5: ***LPBF Operation*** Model.

The ***Coat Powder*** operation model is presented in Figure 6. This operation defines the ***Powder Recoating System*** configuration and the ***Coating Parameters***. The ***Coat Powder*** operation can only have one configuration and set of parameters specified. During the LPBF process both the ***Coat Powder*** and ***Fuse Material*** operations are performed multiple times. Typically, the associate ***parameter specifications*** for these operations will be standardized throughout the build. This model allows for per-operation parameter editing. For instance, if layer n contains many scan paths in comparison to layer n+1, then the ***Return Rate*** parameter of the ***Coat Powder operations segment*** for layer n+1 can be changed to reduce the thermal gradient between the powder layers, and vice versa.

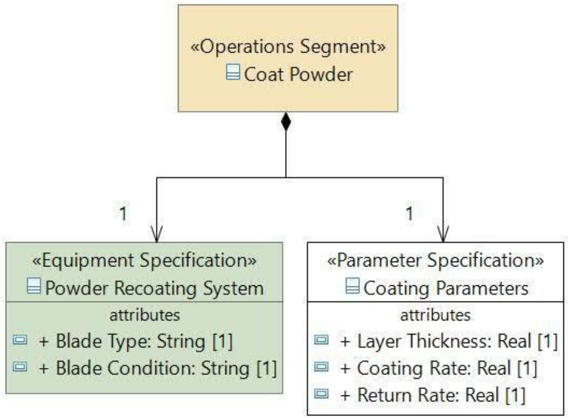

Figure 6: ***Coat Powder*** Model.

The ***Fuse Material*** operation model is presented in Figure 7. This operation is associated with the ***Laser System***, which specifies the laser configuration including the ***Beam Diameter***. Specific ***Part Definitions*** can be associated with the ***Fuse Material*** operation if required. Supports can be defined separately as a ***Part Definition*** and associated using the ***Support ID*** attribute. This allows for different ***Fuse Material*** operations for different parts within a build or their associated supports. For multi-laser systems, a ***Fuse Material operations segment*** shall be defined for each laser and associated with its ID. ***Laser Power*** and ***Scan Speed*** can be defined as global parameters for the ***Fuse Material*** operation or for a specific hatch or contour-type operation. The ***Hatch Operation*** can be instantiated by different types of hatch patterns. This model defines ***parameter specifications*** for either a chess or stripe hatch pattern.

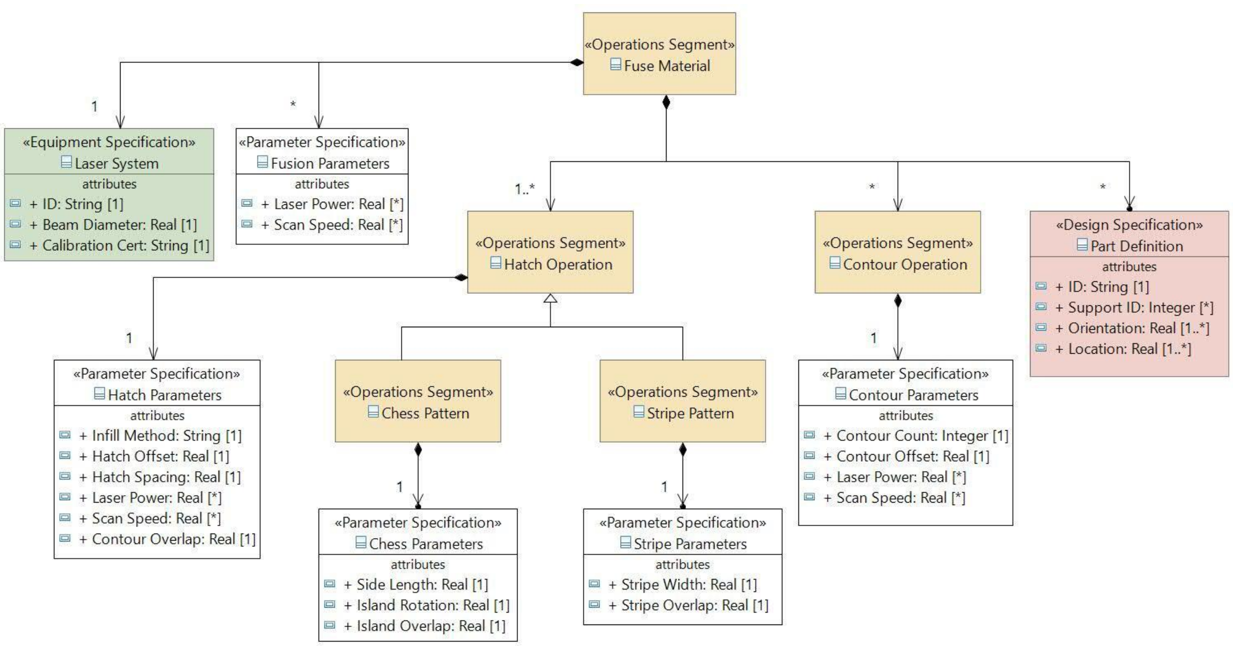

Figure 7: ***Fuse Material*** Model.

Case Study & Discussion

An AM production scenario is planned for a simple block-type component to be manufactured via an LPBF process out of Ti-6Al-4V ELI material. The part see in Figure 8 was designed in CAD and exported in the STEP file format. This part is to be built directly on the build plate. The units used for this scenario are millimeters, degrees Celsius, seconds, and percent relative humidity. The ***Powder Feedstock*** attributes are standard units per the relevant ASTM International test method.

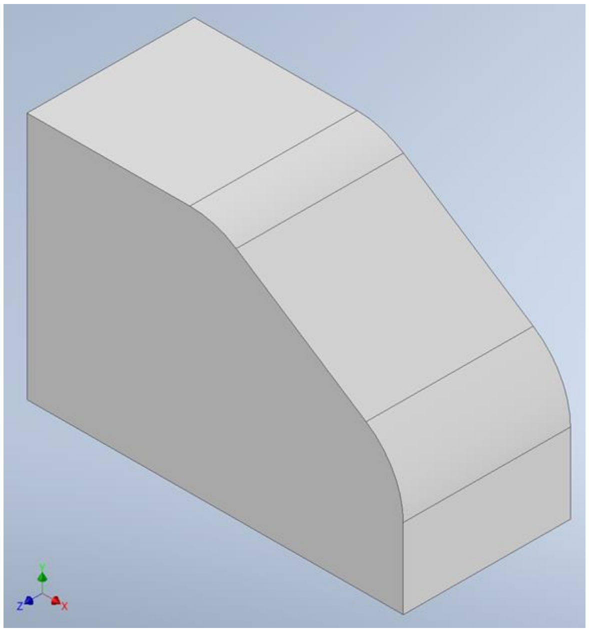

Figure 8: "AA-01" ***Part Definition***.

Figure 9 presents the instantiated ***AM Operation*** definition which defines the higher-level operational controls at the level of the ***AM Work Cell***. One ***AM Operation*** is defined for this production scenario.

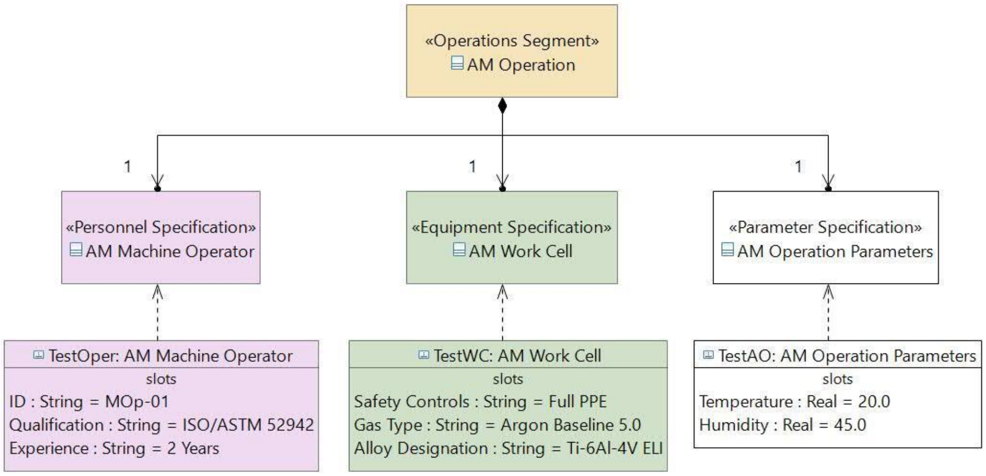

Figure 9: Instantiated ***AM Operation*** Definition.

The instantiated ***LPBF Operation*** definition is presented in Figure 10. This operation associates the ***Build Definition***, consisting of one part, with the LPBF equipment, feedstock material, and machine parameters. The ***Machine Parameters*** specify the controls for the machine operations, whereas the attributes of the ***design***, ***material***, and ***equipment specifications*** detail the information that should be verified by the ***AM Machine Operator*** before beginning production.

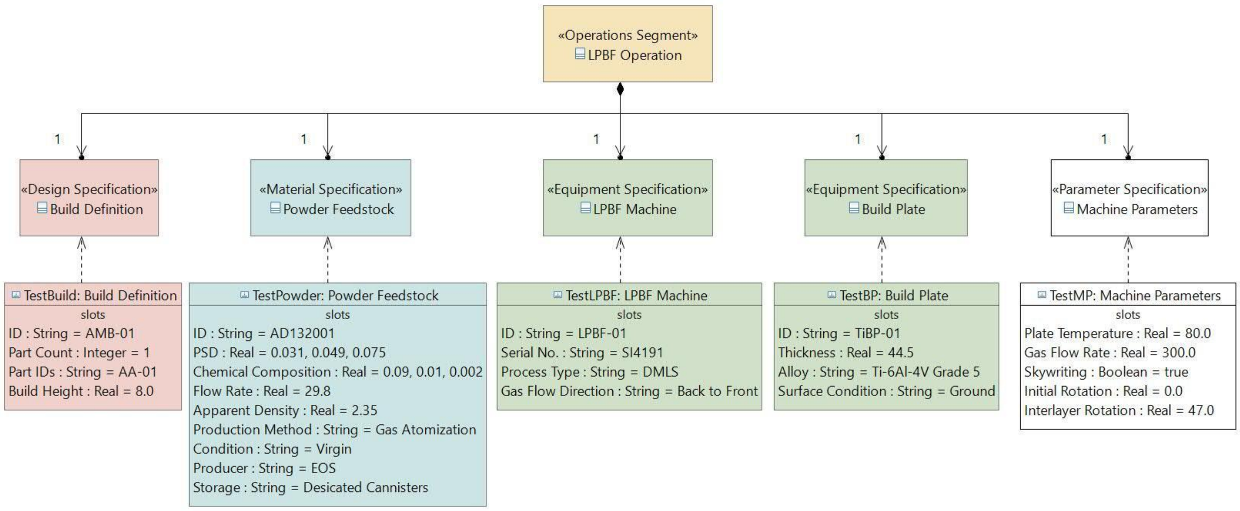

Figure 10: Instantiated ***LPBF Operation*** Definition.

The ***Coat Powder*** operational definition presented in Figure 11 defines the controls for each of the powder coating operations for the full build. The number of powder coating operations to be performed and the number of slices in the build file is a function of the instantiated ***Build Height*** divided by the instantiated ***Layer Thickness***.

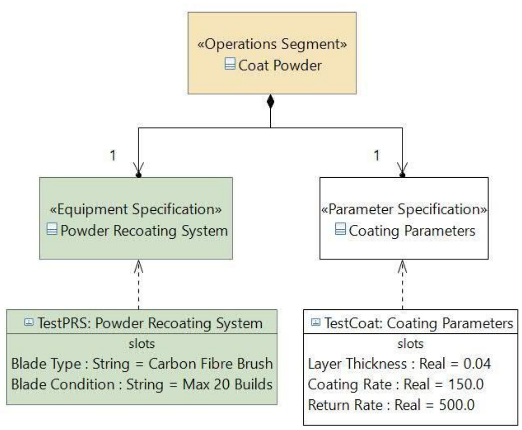

Figure 11: Instantiated ***Coat Powder*** Definition.

The ***Fuse Material*** definition is presented in Figure 12. Two instances of the ***Contour Operation*** are defined for two separate contour scans whereas one instance of the ***Hatch Operation*** is defined for all the hatches for the “AA-01” part.

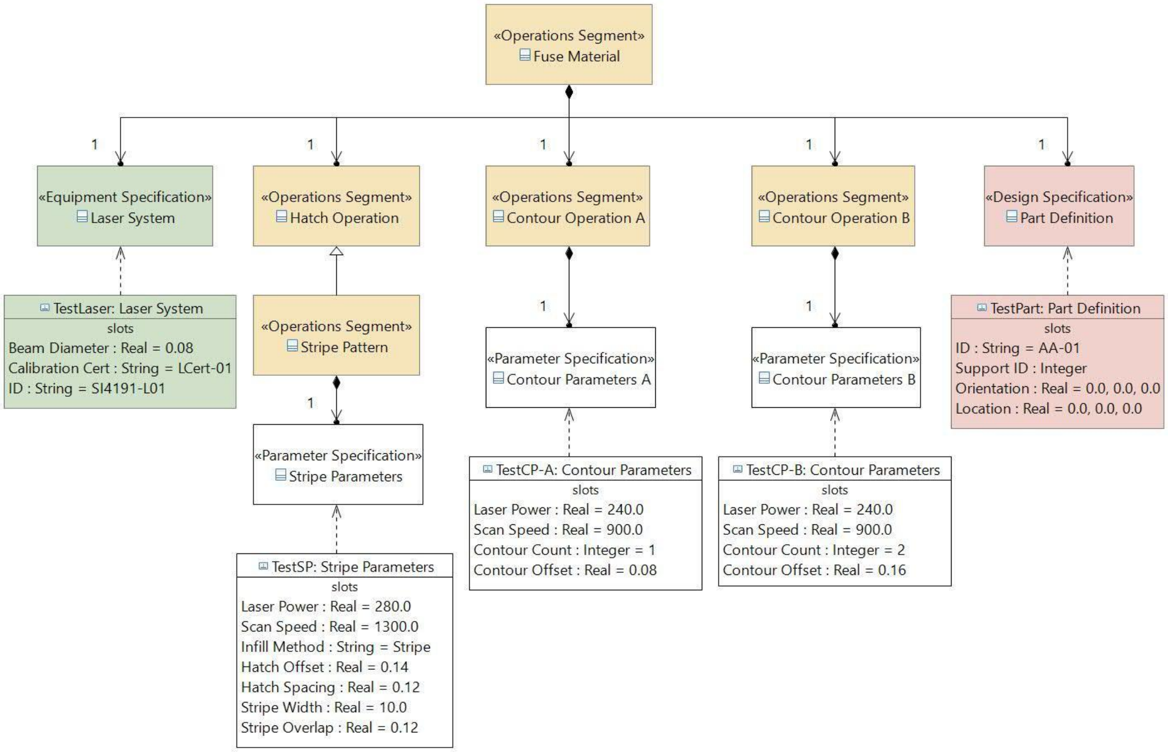

Figure 12: Instantiated ***Fuse Material*** Definition.

The instantiated control data was used to create a CLI file to control the LPBF process. Figure 13 presents a snippet of this created CLI file and a plot of the "Layer 0001" visualizing the laser toolpath. The created CLI file consists of two contours with a striped-type hatching for the infill.

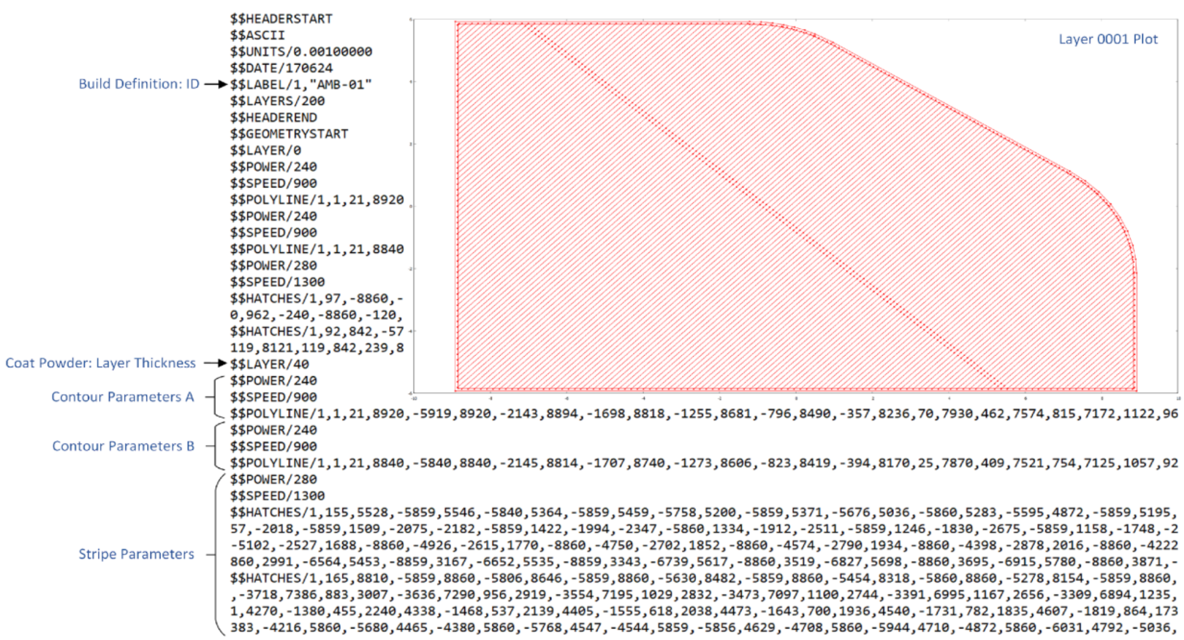

Figure 13: Generated CLI for Laser Toolpaths.

The CLI file does not contain all the information required to control AM operations, nor do STEP-NC files traditionally. The additional information defined in the instantiated SysML models can be used to generate a comprehensive digital manufacturing and control plan in a format best suited for the production organization. Such production plans are integral to production quality and are required for critical applications [15], [20], [21]. Such architectural models provide a means for defining all production system information in a digital and configuration-controlled manner. The proposed model is for production definition information per ISA-95 only [1]. This model shall integrate with production information models per ISA-95 to allow for linkages between specified and measured data to support qualification activities [1].

Operational control models such as the one proposed in this research are designed models, challenges arise during the implementation and enforcement of these controls for physically dominant aspects of production. Such cases typically require the human operator to first interpret the control definition and then perform the required action to either implement the control or check that the specified control is being adhered to. The level of required graduality in terms of production definition information is dependent on the industrial application and regulatory environment. Some applications and industries may not require in-depth operational controls and definitions, such as a fully instantiated ***Fuse Material*** control definition to be defined for production operations, and black-box approaches using commercially off-the-shelf software may be sufficient.

Development and use of production operations models allow for virtual prototyping and assessment of production activities before physical implementation. This approach can enable stakeholders to identify and mitigate risk and assess compliance with industry requirements. This is especially valuable for advanced manufacturing systems such as AM as the capital investment and time required to implement and industrialize these systems is costly. The reference model for AM operational control proposed in this research provides a structure and syntax for integrating physical and digital elements of the production systems. This reference model provides an architecture for implementing operational digital twins for metal AM processes.

Future work should investigate the applicability of the proposed approach for defining and applying production controls to other AM technologies and post-processing techniques to incorporate controls along the whole production processes for a component. Additionally, integration of this model with simulation software should be investigated. This can enable the transferal of critical control parameters and allow the simulation of production operations to optimize the control parameters before configuration controlling the production control definition.

Conclusion

Control of metal additive manufacturing operations is integral to controlling material and part quality. Additive manufacturing machines and processes are complex and involve many variables and parameters. This complexity is exacerbated by the lack of standardized terminology and approaches for control definitions. This research proposes a model-based operational control architectural model for metal additive manufacturing that leverages the ISA-95 and STEP-NC reference architectures. This model specifies categories of operations, production elements, and associated parameters required for ensuring quality. The proposed model was utilized for defining production and operational controls for a production scenario and to generate a machine-readable build file. This reference model integrates physical and digital elements of additive manufacturing production and provides an operational digital twin architecture.

Acknowledgments

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