IOP Conference Series: Materials Science and Engineering

Toward semantic standard and process ontology for Additive manufacturing

To cite this article: S Gouttebroze *et al* 2023 *IOP Conf. Ser.: Mater. Sci. Eng.* **1281** 012014

Toward semantic standard and process ontology for Additive manufacturing

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Abstract. Advanced modelling of additive manufacturing often requires the combination of models at multiple scales and multi-physics. Therefore, building the modelling workflow describing the process is complicated. The modelling is also only a part of the innovation process and must be connected to practices, experimental work, and characterisation. Efficient communication and data exchange between the different actors could quickly become a challenge. Recent developments in the frame of the EMMC (European Material Modelling Council) and in the EU project OntoTrans points toward the early integration of semantic description and the creation of dedicated domain ontologies. This require an unambiguous and consistent use of terms and definitions for various concepts within each field of technology, and international standards is an available source for structured technical terms and definitions. For additive manufacturing (AM) the international standard ISO/ASTM 52900 "Additive manufacturing - General principles - Fundamentals and vocabulary" is the internationally recognised source for terms and definitions. Basing the ontology on the AM terminology standard will greatly facilitate integration of AM processes as a part of an industrial manufacturing system. Therefore, the present work attempts to harmonise the standard terminology and the ontology concepts. Then, to improve the impact and connection to material science, the concepts will be connected to a microstructure domain ontology and to the top- and middle-level ontology EMMO. The conceptualisation and application of the ontologies will be illustrated through simple examples of process and material modelling.

1. Introduction

Additive manufacturing (AM) is becoming a reliable manufacturing route through the improvement of equipment, procedures, and feedstock. Normally a manufacturing process chain based on AM requires a series of operations and sub-processes besides the actual AM process. Preparations and post-processing operations can have a critical influence on the properties of the final product and therefore a combination of multiple models at multiple scales and multi-physics are necessary. This modern production method requires a high level of automation and integration of models and simulations to design the part, configure and automatise the process, and predict the performance. In industrial applications, processes such as laser-based powder bed fusion (PBF-LB) require both production time and high-quality feedstock material that can be quite expensive. Failure in production, or a failed product, can have a high impact on total production costs due to the wasted time and material, in particular for customised or small series manufacturing which is a common use for AM. Establishing reliable procedures and gathering expert knowledge has been a major focus on the last decade's work. The need to relate the component properties to process choices like support structures (internal and external), slicing, orientation, laser path, and laser parameters has led to multiple research studies and the development of numerical models. This knowledge and practical experience must be spread and reused to facilitate the industrial application of AM. Ideally this knowledge can be formalised and stored in a knowledge graph. This step is also required for the implementation of smart manufacturing where the next generation of manufacturing systems will have cognitive capabilities and the ability to control the execution of the task based on sensor measurements and reasoning on existing formal knowledge. The developments of ontologies for material, process and product are essential to convert existing knowledge into machine-readable, logical relations.

Per definition, international standards may contain product-performance requirements, describe recommended or required best practice testing procedures, or specify the content of services and how they should be performed. They can also include terminology. The aim of standards is to provide clear guidelines for consistent function and quality, improve processes, transparency, and comparison. Clarity in communication is critical, and therefore the use of vocabulary, including terms and their definitions, needs to be consistent and coherent throughout all standards on any given topic. This requires that a terminology standard is developed and widely accepted by consensus in the community. The development of international and industrial standards is mostly conducted through dedicated standard development organisations (SDOs) such as ISO, CEN/CENELEC, ASTM International, ASME, and other national or industry association-driven organisations, as reviewed by Kawalkar *et al.* [1].

On the other hand, an ontology represents knowledge as a map or graph of concepts within a domain and their relationships. The ontology is often expressed as an annotated machine-readable knowledge graph. The ontology is used to associate meaning to data (like measurements, procedure description, models, etc.), provides links between data, and allows for machine reasoning. Ontologies have proved themselves in various domains as being a valuable tool for solving knowledge and interaction problems. Still, in the manufacturing domain, ontologies are at an early development stage. Sanfilippo *et al.* [2] made a comparison of different ontologies and proposed a new one based on DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering) [3]. In this work, the ontology will be related to the EMMO [4]: “The Elementary Multiperspective Material Ontology (EMMO) is the result of a multidisciplinary effort within the European Material Modelling Council (EMMC), aimed at the development of a standard representational ontology framework based on current materials modelling and characterisation knowledge.” EMMO development is based on description of the world anchored in physics and material sciences, integrating for example the concept of quantum of energy. A key advantage of EMMO is its inherent connection to material and process modelling that will facilitate the communication and integration of physics-based software.

The present work addresses AM technology and will therefore focus on extracting information only from the international standard for terminology in AM technology ISO/ASTM 52900 [5]. Building an ontology based on a published standard will require a parsing of the text to extract terms and definitions, and additional categorisation of the content. The aim is to develop a semi-automated procedure to build an ontology based on an online html version of the published terms and definitions. Then the ontology is linked to existing top-level and domain ontologies to provide a more comprehensive description. The meaning of and benefit for interoperability are described in the third section. Finally, the ontology is applied to describe existing research work.

2. Standardisation and ontology

The terms and definitions of ISO/ASTM 52900:2021 are available online through ISO’s online browsing platform [6]. This is in the form of a structured html document, which enables automation of a part of the processing with the id and class of the html document. Automation is important to future application of the same methodology to other standards, and also to update the ontology following the upcoming revisions of the document. The main structure is presented in Figure 1. The terms are divided into three categories: general, processing, and parts. These sections are formed of the terms necessary to describe some key concepts but are not parenthood relations. For example, the term "3.12.4 final inspection" is a process and therefore not a subclass of the term "3.9.1 part" while "3.10.1 prototype" could be considered as a subclass of "3.9.1 part". The first step of the html document parsing is then to extract that section structure and at the same time the grammar information (as seen in Figure 2, the grammatical type is indicated).

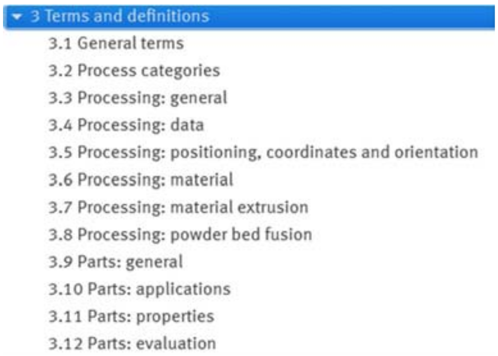
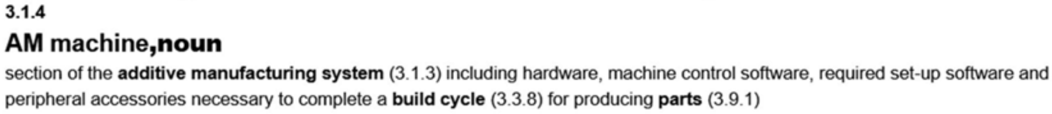

- 3 Terms and definitions
  - 3.1 General terms
  - 3.2 Process categories
  - 3.3 Processing: general
  - 3.4 Processing: data
  - 3.5 Processing: positioning, coordinates and orientation
  - 3.6 Processing: material
  - 3.7 Processing: material extrusion
  - 3.8 Processing: powder bed fusion
  - 3.9 Parts: general
  - 3.10 Parts: applications
  - 3.11 Parts: properties
  - 3.12 Parts: evaluation

Figure 1. ISO/ASTM 52900:2021 structure for terms and definitions

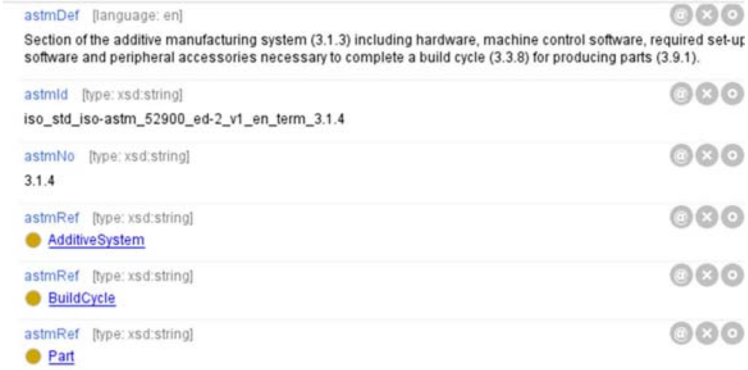
The definition of a term also often includes references to other terms as illustrated in Figure 2. The procedure used to generate the ontology does not include language analysis and therefore will not extract the exact type of relation between the terms or the constraints. This data needs to be added manually later. For now, as illustrated in Figure 3, the procedure will create an ontology class that includes the definition, an id, a section number, and a list of term referenced in the definition. Please note that the terms have been replaced by the ontology concepts based on the section number. In the absence of defined relations, this information is kept as annotation of the class. Please note that as a convention, ontology classes will be written in Italic in the following sections.


3.1.4

AM machine,noun

section of the **additive manufacturing system** (3.1.3) including hardware, machine control software, required set-up software and peripheral accessories necessary to complete a **build cycle** (3.3.8) for producing **parts** (3.9.1)

Figure 2. ISO/ASTM definition for AM machine.


astmDef [language: en]
Section of the additive manufacturing system (3.1.3) including hardware, machine control software, required set-u
software and peripheral accessories necessary to complete a build cycle (3.3.8) for producing parts (3.9.1).

astmId [type: xsd:string]
iso_std_iso-astm_52900_ed-2_v1_en_term_3.1.4

astmNo [type: xsd:string]
3.1.4

astmRef [type: xsd:string]
● AdditiveSystem

astmRef [type: xsd:string]
● BuildCycle

astmRef [type: xsd:string]
● Part

Figure 3. Ontologised definition of AM Machine

At this point the ontology structure reflects the grammatical information (*GrammaticalCategorisation*) and the paragraph structure (*ThematicCategorisation*). The next step is to categorise the concepts according to higher level concepts, called bridge concepts (as defined in

OntoCommons [7]). These higher-level concepts are ideally not new but related to established ontologies. We have defined 7 categories as presented in Figure 4.

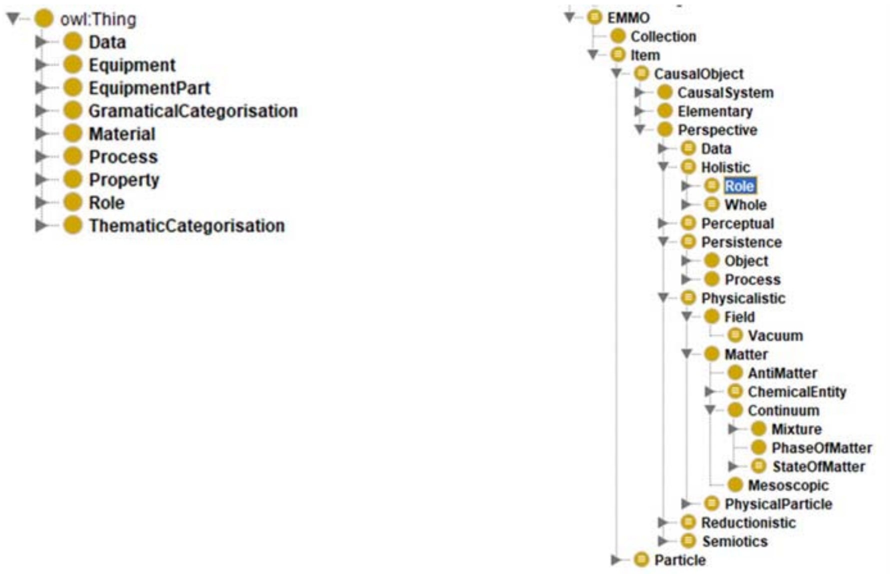


Figure 4. Main classes for the domain ontology for Additive manufacturing (left) and the top ontology EMMO (right)

All the previously parsed concepts are, manually, either defined as subclass of these categories or subclass of an existing class. For example, *Pellets* is defined as a subclass of *Feedstock* which is a subclass of *Material*. These categories represent different perspectives to describe the real world. It has been formalised in the *Perspective* class in EMMO. For example, *Role* is a subclass of *Holistic* perspective defines as "A holistic perspective considers each part of the whole as equally important, without the need to position the parts within a hierarchy (in time or space). The interest is on the whole object and on its parts (how they contribute to the whole, i.e., their roles), without going further into specifying the spatial hierarchy or the temporal position of each part." Similarly, *Process* is seen in the *Persistence* perspective: "The interest is on the 4D object as it extends in time (process) or as it persists in time (object): object (focus on spatial configuration) or process (focus on temporal evolution)." It is important to remember that the concept can be seen through different perspectives. For example, the laser is an equipment part that has a role (providing energy to melt the powder) but is also made of matter and is an assembly of components (with spatial positions and parthood relations).

The relation between the ISO/ASTM classes and the EMMO classes is important to harmonise the development and facilitate the extension of the capabilities. As illustrated in Figure 4, EMMO is still very generic, but domain ontologies have been built based on that logical representation. In the application section, we will see how part of the information used to describe an AM study is outside the scope of the ASTM standard (and so not included in the domain ontology generated from it), therefore requiring to add terms from a domain ontology for microstructure.

3. Data and interoperability

Interoperability (from latin, inter = between and operari = to work) is the ability of two or more systems to exchange information between them through a *common representational system* to perform a complex work that cannot be done by each single system alone. The presence of a common representation system provides the highest level of generalisation and replaceability and means that no privileged one-to-one connection between two system types should be implemented within the interfaces. In principle, in an interoperability scenario, one system can ignore the details about other systems. Figure 5 illustrate the difference between interoperability and compatibility. C*ompatibility* (from latin, cum = with and passus = to suffer) is the ability of two or more systems to establish a one-to-one connection between them, which is usually due to strong similarities in their internal representations that facilitate mutual understanding (e.g. for software this usually happens when systems are parts of a set of tools provided by a common developer) (Figure 5b). In a compatibility scenario, systems are fully aware of the type and identity of the other connected systems.

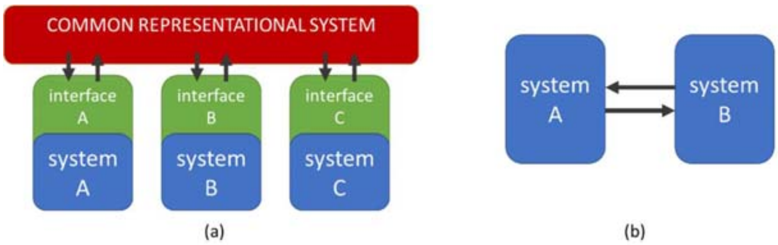


Figure 5. Interoperability (a) versus compatibility (b).

Interoperability can be at several semantic levels, such as scientific community level, user case level and numerical level. To support interoperability between experts from different scientific communities and different digital systems/simulation tools, the common representational system language must be understandable by both humans and machines. The ontological framework described in the last section serve exactly this purpose – to be a common representational system that is interpretable by both humans and machines.

There are different approaches for how to utilise ontologies in interoperability platforms. The SimPhoNy Open Simulation Platform [8] achieves interoperability by creating a representation using a set of connected classes in the Python programming language. This allows the user of SimPhoNy to seamlessly connect simulation engines, databases, and data repositories. However, for this to work, there must first exists a complete ontological description of the use case.

In the interoperability framework targeted by this work, we take another approach: we focus on the user and easy onboarding. The starting point is separation of concerns. Figure 6 shows an interoperability case where data from a database is used as input to a model. The database and model were developed completely independent of each other. The database provider knows the structure of the database but is not an expert on ontologies. The same is the case for the modeller, this person knows the input that the modelling tool expects, but not the details of the ontology. Instead of demanding these people to describe the data they provide or expect, they are only asked to describe their respective data in terms of simplistic, but formalised data models, whose structures can be made very similar to the database or model input. This makes it easy for the data provider/modeller or maybe even an external software engineer, to write a driver that can create an instance of data model A populated with data from the database or a driver that can serialise an instance of data model B to the form expected by the model. By mapping the properties of these data models to shared concepts in the ontology, it is now possible for the interoperability system to correctly create the input to the model from data in the database. It is only the ontologist that needs to know the details of the ontology and how properties can be converted from one concept to another. The low-level implementation of drivers for the database or modelling tool can be done by a software engineer. The ontologist can also help adding new concepts to the ontology as required by the domain experts.

A semantic interoperability framework based on the principles described above has been developed in a range of EMMC-related EU projects, especially OntoTrans [9] and OpenModel [10]. The main component of this framework is OTEAPI (Open Translation Environment Application Programming Interface) [11], which allows to document different data sources or data sinks in terms of reusable so-called partial pipelines, that can be stored in a knowledge base.

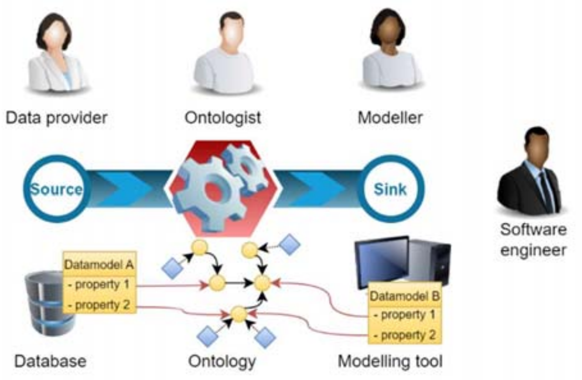


Figure 6. Achieving interoperability by separation of concerns.

A pipeline, like the one shown in Figure 6, can easily be created by connecting a partial pipeline for a data source with another partial pipeline for a data sink. This gives the user a high degree of freedom to mix and match data sources and modelling tools in a very flexible way. It is also possible to combine the pipelines into complex modelling workflows. Other important components of this semantic interoperability framework include the ontology, DLite [12] (an interoperability framework based on data models) and tripper [13] (a package that provide a common interface to the ontology regardless of how it is stored).

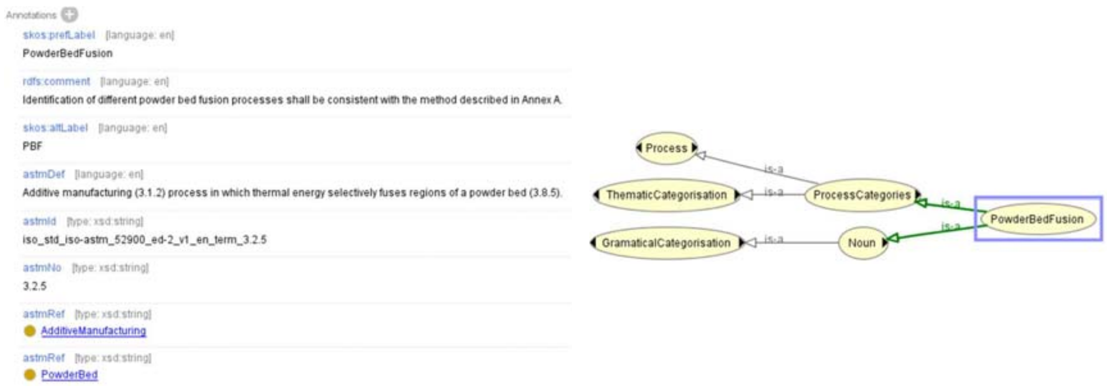
4. Application

The AM domain ontology [14] based on the ISO/ASTM 52900 standard can be applied to describe current research work on AM. As an illustration, we have selected three papers previously published by colleagues from SINTEF and NTNU (Norwegian University of Science and Technology) colleagues with slightly different perspectives. The first paper [15] focuses on process development and improvement. The AM description takes a significant part of the introduction section and the section on Materials and Methods. The second paper [16] is an intermediate paper linking the process to the properties. The focus on the AM process is smaller and seen more through the sample used for mechanical analysis. Finally, the third paper [17] focuses on the properties of the material produced with AM. The paragraph describing AM process parameters is even shorter and the second section is named only “Methods” (instead of “Materials and Methods”). It reflects the variations in the intention of the authors. For all papers, the interpretation of the results also includes references to AM terminology.

This case illustrates the importance of the common terminology and domain ontology as for all of them the description of the process should be understandable by all the actors to allow reproducible research. We will now attempt to convert the natural language description of the AM process into a semantic description relying on our new ontology. We will not completely cover all the data sets as it might require additional developments in the ontology and other application ontologies. Still, we will try to illustrate the necessary connection to other ontology in the second section.

4.1. Process and equipment

These studies are considering only laser powder bed fusion (PBF-LB) as the manufacturing process. The domain ontology used the term *PowderBedFusion* (see Figure 7). This term is referring to *AdditiveManufacturing* and *PowderBed*. Thus, it reflects that it is a manufacturing process, which could be inferred from the relations, and that it is applied to a material which is first considered as a geometrical domain as seen in Figure 8. This example illustrates as well that the ontology extracted from the standard using the current methodology is incomplete as it does not define explicit relations between the main component of the system, namely the powder material and the equipment.



Annotations

skos:prefLabel [language: en]
PowderBedFusion

rdfs:comment [language: en]
Identification of different powder bed fusion processes shall be consistent with the method described in Annex A.

skos:altLabel [language: en]
PBF

astmDef [language: en]
Additive manufacturing (3.1.2) process in which thermal energy selectively fuses regions of a powder bed (3.8.5).

astmId [type: xsd:string]
iso_std_iso-astm_52900_ed-2_v1_en_term_3.2.5

astmNo [type: xsd:string]
3.2.5

astmRef [type: xsd:string]
● AdditiveManufacturing

astmRef [type: xsd:string]
● PowderBed

Figure 7. Definition and relations for the class PowderBedFusion

skos:prefLabel [language: en]
PowderBed

skos:altLabel [language: en]
PartBed

astmDef [language: en]
Location in an additive manufacturing system (3.1.3) where feedstock (3.6.6) is deposited and selectively fused by means of a heat source or bonded by means of an adhesive to build up parts (3.9.1).

astmId [type: xsd:string]
iso_std_iso-astm_52900_ed-2_v1_en_term_3.8.5

astmNo [type: xsd:string]
3.8.5

Figure 8. Definition and relations for the class PowderBed

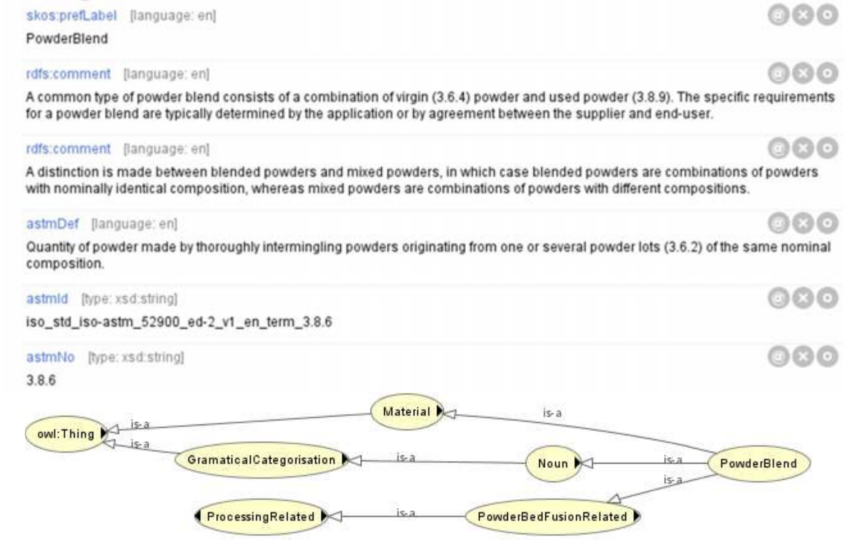
The selected papers focus on the effect of anisotropy induced by the manufacturing process itself. From [15], “flat tensile specimens were produced in three sets, each consisting of 11 specimens built at different orientations. The sample orientation with respect to the build plate starts at horizontal (0°) increasing to vertical (90°) with 15° increments.” The concept *BuildPlatform* is defined as an *Equipment,* but it has plural meanings in the previous description as it also refers to the *BuildSurface* (for the first layer) defined as a geometrical object. The proper definition of the orientation and position require as well as the definition of *BuildOrigin* and (*XAxis*, *YAxis*, *ZAxis*). Then the *PartPosition* and *PartReorientation* are defined and related to *PositionVector* defined in EMMO.

Important process parameters such as Laser power, Layer thickness, Hatch spacing, and Scan velocity are specified in the publication but not part of this standard. The terms "laser power" or "layer thickness" are considered as self-explanatory, and something that a qualified user of any AM standard would understand without the need for a definition, and ISO Directives states that they should not be defined in terminology standards. Only the generic concept of *ProcessParameters* is present. Nevertheless, EMMO already includes physical quantities. For example, *Power* is defined and associated with *PowerDimension* with the symbolic value "T-3 L+2 M+1 I0 Θ0 N0 J0" for Time - Length - Mass - Electric Intensity - Temperature - Amount - Luminous Intensity. *LayerThickness* would then be defined as a subclass of *Length* and inherit its properties and relations.

In addition, the samples are submitted to different post-process operations. In the standard, only *PostProcessing* is defined as a generic category. In the study, only heat treatment and HIP are used. These processes are generic and not specific to AM and therefore would naturally belong in another ontology.

4.2. Material and properties

The standard also allows us to describe the powder material. The main class is *Feedstock* that covers multiple AM processes. For PBF-LB, the powder characteristics are essential. The standard allows to specify the source of the powder (via *FeedstockManufacturer* and *FeedstockSupplier*) but more importantly indicate the possible reuse with *Virgin* and *UsedPowder*. In addition, the powder preparation is differentiated with *PowderBlend* and *PowderMix* as illustrated in Figure 9.



Annotations

skos:prefLabel [language: en]
PowderBlend

rdfs:comment [language: en]
A common type of powder blend consists of a combination of virgin (3.6.4) powder and used powder (3.8.9). The specific requirements for a powder blend are typically determined by the application or by agreement between the supplier and end-user.

rdfs:comment [language: en]
A distinction is made between blended powders and mixed powders, in which case blended powders are combinations of powders with nominally identical composition, whereas mixed powders are combinations of powders with different compositions.

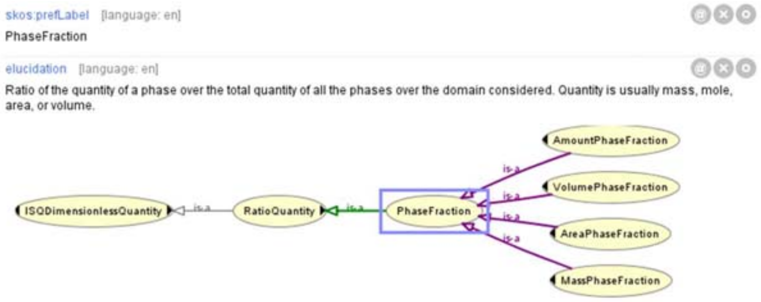
astmDef [language: en]
Quantity of powder made by thoroughly intermingling powders originating from one or several powder lots (3.6.2) of the same nominal composition.

astmId [type: xsd:string]
iso_std_iso-astm_52900_ed-2_v1_en_term_3.8.6

astmNo [type: xsd:string]
3.8.6

Figure 9. Definition and relations for the class PowderBlend

The description of the powder characteristics and part microstructure are not covered by the standard. Therefore, we include an additional microstructure ontology [18] based on EMMO. It allows to define the powder composition using the concept *ChemicalComposition*. The anisotropy of the microstructure also necessitates the concepts of matrix (*MicrostructureMatrix*), *Grain*, *Orientation* and *EulerAngles* to describe the texture. The microstructure ontology includes *PhasesFraction* (see Figure 10), *Dendrite*, *SecondaryArmSpacing*, *GrainBoundary* to specify the phase distribution and grain structure.



skos:prefLabel [language: en]
PhaseFraction

elucidation [language: en]
Ratio of the quantity of a phase over the total quantity of all the phases over the domain considered. Quantity is usually mass, mole, area, or volume.

Figure 10. Definition and relations for the class PhaseFraction

The description of the mechanical properties would require an ontology as well which is not in place in the framework of EMMO.

4.3. *Perspective on process and component modelling*

In the previous sections, the experimental set-up and the process steps have been partly described using the AM ontology based on the standard and complementary ontologies. This must be seen as the first step to document semantically an existing process and component. The second step is to enable semantic interoperability for the simulation tools. For example, the definition of the laser power and path according to the standard should allow the automatic generation of the input file for the process simulation by the application of a wrapper layer that will connect the ontological concept to a variable in the model and its syntax for the input file. Similarly, the microstructure description could be correlated and compared with model prediction (like average model for grain size prediction or direct simulation with phase field). The systematic storage of data from measurements, experiments, and simulation as part of a knowledge graph would facilitate optimisation studies. The optimisation done by Azar et al. [19] requires linking surface characterisation and fatigue modelling by representing the surface roughness effect on crack initiation. Sharing common concepts and representing data in the appropriate format for the different communities is a key to enhance interdisciplinary collaboration.

4.4. Reasoning

As previously mentioned, this new ontology only includes information present in the standard and therefore does not pretend to generate a fully consistent ontology. Nevertheless, it allows us to identify the gap between standard documents and functioning ontologies. The semantic storage of all relevant information and measurements for the process, material, and part allows to build a massive knowledge graph. Such a knowledge graph could include as well other standards specifying the parameters for efficient production of specific components or structure. The extension with techno-economic data will also unlock production optimisation and decision support (see examples from Nagy *et al.* [20]).

Automated reasoning could be applied when semantic data is based on ontologies. Rules could be extracted to determine the ability to produce a component. For example, a rule could state that if a part is made of aluminium and its minimum wall thickness is greater than or equal to 3 mm, then it can be manufactured additively with these process parameters and these powder composition and sizing. These rules are deduced from the data stored in the knowledge and can later be applied to assess a design/production proposal automatically. A part that satisfies this rule will become a subclass of the *AMfeasible* class.

5. Concluding remarks

This paper presents the initial effort to partly automatise conversion of the ISO/ASTM AM terminology standard into a functioning ontology based on EMMO. The proper formatting of the online document allows us to extract important information and document structure. Nevertheless, the topics and categorisation of terms published in the present edition of this standard is not sufficient to build a complete ontology. Terminology standards and ontologies are developed to serve different purposes, and clearly this also means that the structures and functionalities are not perfectly matched. For building ontologies, it is necessary that the concepts defined in the standard are structured based on defined subclasses of high-level concepts. We have demonstrated that step and its linking to the top-level ontology EMMO. The AM ontology was then applied to describe existing research work. The focus on production of the selected standard does not cover all the concepts used by the referenced paper. It reveals the need for a broader development of ontologies dedicated to AM and materials science. The addition of the microstructure ontology developed in the frame of the EMMC enabled us to cover most of the microstructure concepts.

The growing integration of material and process modelling in component design and manufacturing will require the coupling of multiple models. The present work showed partly how the development of domain specific ontologies will enable semantic interoperability, therefore greatly accelerating the integration of new models in simulation workflows. In the future, it is expected that all numerical models will need to semantically describe their input and output to be broadly use and integrated in modelling software marketplaces.

The terms and definitions of ISO/ASTM 52900 are freely available through the ISO Online Browsing Platform, similarly the AM domain ontology is released on a public repository under the Creative Commons Attribution 4.0 International license (CC BY 4.0). It allows any manufacturer, designer, modeler to rely on the common vocabulary and integrates semantic at no cost. Standards are more than just terms definition, the fundamental need for clarity, consistency and coherency, as well as assuring the openness and transparency of the process, and a clear procedure for establishing consensus agreement and the publication of the standard requires a significant administration and clear directives, and this costs money. Currently the users pay for accessing the standards documents, so that the costs are covered by those who need, use and benefit from them. In the future, standards will need to be integrated in the digital world within knowledge graphs in order to enable smart manufacturing. This work can be seen as an early step in that direction where research work begins to be documented semantically based on ontologies covering production, material, processes. Later, the user could buy fully ontologised standards and ensure their application by computer reasoning on the stored data.

In the short term, we will aim at expanding the existing ontologies to cover the necessary measurements, simulations, and experimental set-up to completely describe our work. The objective is also to strengthen the connection to EMMO by exploiting the symbolic description of models and enhance interoperability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Acknowledgments

This research work is funded by the SFI Manufacturing “Centre for competitive high value manufacturing in Norway” (grant number 237900) and SFI PhysMet “Center for sustainable and competitive metallurgical and manufacturing industry” (grant number 309584/F40) with support from the Research Council of Norway and the industrial partners. The interoperability work and development of EMMO was done through the project OntoTRANS, H2020-DT-NMBP-10-2019, with support from the EU commission (grant agreement 862136).

References

[1] Kawalkar R., *et al.*, 2022, Materials Today: Proceedings 50, pp. 1983–1990
[2] Sanfilippo E., *et al.*, 2019, Computers in Industry, 109, pp.182-194.
[3] Borgo S., and Masolo C. “Foundational choices in DOLCE”. In Handbook on Ontologies, S.Staab and R.Studer, Eds. Springer Verlag Berlin Heidelberg, 2009.
[4] https://github.com/emmo-repo/EMMO
[5] "ISO/ASTM 52900:2021Additive manufacturing — General principles — Fundamentals and vocabulary", International Organization for Standardization (ISO) 2021, ASTM International 2021.
[6] https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-2:v1:en
[7] OntoCommons, https://ontocommons.eu/
[8] SimPhoNy, https://simphony.readthedocs.io/
[9] OntoTrans, https://ontotrans.eu/
[10] OpenModel, https://open-model.eu/
[11] OTEAPI, https://emmc-asbl.github.io/oteapi-core/
[12] DLite, https://github.com/SINTEF/dlite
[13] Tripper, https://emmc-asbl.github.io/tripper/
[14] https://raw.githubusercontent.com/emmo-repo/doam/main/astm52900.ttl
[15] Hovig E, *et al.*, 2018, Advances in Materials Science and Engineering, Article ID 7650303
[16] Hovig E, *et al.*, 2021, The International Journal of Advanced Manufacturing Technology, 114:1359–1372
[17] Solberg K, *et al.*,2021, International Journal of Fatigue 149, 106229
[18] https://github.com/emmo-repo/domain-microstructure
[19] Azar A., *et al.*, 2021, Rapid Prototyping Journal, Vol. 27 No. 2, pp. 256-267
[20] Nagy L., *et al.*, 2021, Complexity, Volume 2021, Article ID 8603515.