An Ontology for Defect Detection in Metal Additive Manufacturing

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Abstract

A key challenge for Industry 4.0 applications is to develop control systems for automated manufacturing services that are capable of addressing both data integration and semantic interoperability issues, as well as monitoring and decision making tasks. To address such an issue in advanced manufacturing systems, principled knowledge representation approaches based on formal ontologies have been proposed as a foundation to information management and maintenance in presence of heterogeneous data sources. In addition, ontologies provide reasoning and querying capabilities to aid domain experts and end users in the context of constraint validation and decision making. Finally, ontology-based approaches to advanced manufacturing services can support the explainability and interpretability of the behaviour of monitoring, control, and simulation systems that are based on black-box machine learning algorithms. In this work, we provide a novel ontology for the classification of process-induced defects known from the metal additive manufacturing literature. Together with a formal representation of the characterising features and sources of defects, we integrate our knowledge base with state-of-the-art ontologies in the field. Our knowledge base aims at enhancing the modelling capabilities of additive manufacturing ontologies by adding further defect analysis terminology and diagnostic inference features.

Keywords: Knowledge Representation, Ontologies, Additive Manufacturing, Powder Bed Fusion

1. Introduction

Fully automated manufacturing systems, as well as production-as-a-service frameworks, represent a cornerstone of Industry 4.0 applications\cite{27}. In this context, additive manufacturing (AM), and specifically metal additive manufacturing (MAM), is particularly suited to industrial paradigms based on automation, flexibility, and efficiency. Indeed, MAM can be considered as a native digital technology, providing a seamless workflow from the digital design environment to the final product, which can be potentially completed without any human intervention\cite{30}.

However, a broader adoption of MAM technologies in industry is still hindered by such factors as: (i) lack of widely adopted standardisations and specifications of material properties, machines, and processes\cite{40}; (ii) lack of adequate digital infrastructures, and interoperability issues between different production environments\cite{7}; (iii) lack of accessible interfaces providing process information that is easily interpretable by non-experts\cite{47}; (iv) lack of advanced control systems capable of automatically adjusting, at run-time, the production parameters\cite{54}; (v) challenges in quality assurance due part accuracy and variability\cite{48}.

Thus, achieving semantically transparent and interoperable data sets and systems, to address Points (i), (ii) and (iii) above, is arguably of paramount importance. In this direction, several approaches based on ontology engineering and knowledge representation techniques have been proposed\cite{29, 10, 66, 67, 60}. Broadly conceived as formal specifications of conceptualisations over a domain of interest, computational ontologies (cf.\cite{33} and references therein) have been in particular investigated as a tool to improve interoperability of additive manufacturing systems that involve human-intensive and domain-expert knowledge management tasks (cf. Section 2 for a literature survey).
To the best of our knowledge, however, despite the number of domain-specific ontologies proposed in the literature to address interoperability issues, less attention has been devoted to another crucial aspect of AM applications, in particular of Powder Bed Fusion (PBF) MAM: that of defect diagnosis and correction. PBF is a layer-by-layer process, where a layer of metal powder is spread by means of a roller on top of a build plate, and metal powder particles are selectively melted by means of a localised moving laser heat source [26]. At industrial level, PBF MAM is a widespread technology, due to its capability to deliver parts with high surface quality and remarkable mechanical properties. Nonetheless, the localised nature of the melt pool induces rapid melting-solidification cycles that are responsible for part deflections and residual stresses [9]. Moreover, due to their multi-scale and multi-physics nature, phenomena involved in PBF processes are difficult to control. Finally, the overall process is characterised by complex and not yet fully understood relationships among material microstructure, part geometry, process parameters, and mechanical properties and performances [70]. Such issues can lead to process-induced material discontinuities, e.g., lack-of-fusion and keyhole porosity, balling, crack and delamination [22].

Even if these process-related defects play a key role influencing part properties and performances (e.g., elastic and elastoplastic behaviour, ultimate tensile stress, and fatigue life), an ontology-based representation of MAM defects, together with their main properties surveyed in the literature [11], is not yet available. Such a principled approach, integrating observational data with formalised domain knowledge to determine the causality links and the complex process-structure-property relationships in manufacturing processes, represents an important preliminary step for the development of reliable monitoring and control systems capable of addressing Points (iv) and (v) above [20].

Our contribution aims at filling this gap, by introducing the novel DefectOnt\(^1\) ontology for MAM, specifically PBF-based, defects. This ontology relies on a modular structure, and it aligns with other upper and domain-specific ontologies from the literature, to favour development, interoperability and maintenance. It includes axioms covering the following dimensions: (i) MAM-based categories of defects and related properties; (ii) spatial notions to express geometrical and topological characteristics; (iii) dimensional characteristics requiring a vocabulary of metrological terms; (iv) sensor-related concepts for observational properties. DefectOnt is implemented in the OWL 2 [32]\(^2\), using the open-source Protégé ontology editor [42]\(^3\).

The present article is organised as follow. In Section 2, we discuss related work on MAM defects and AM ontologies. Then, in Section 3, the design methodology and the development phases of our MAM defect ontology are described. In Section 4, we illustrate the DefectOnt ontology, presenting in detail the modules that constitute it. Finally, in Section 5, we discuss future research directions and the main conclusions of the present work.

2. Related work

2.1. MAM-related literature

Malekipour and El-Mouayri [53] identify, analyze, and classify the most common defects in PBF MAM, defining the relationships among defects and their contributing parameters. To develop a suitable online monitoring control strategy, defects are organized into categories based on their manufacturing features and control purposes. Kyogoku and Ikeshoji [46] review the literature regarding defect generation mechanisms in PBF processes and their mitigation strategies. Snow et al. [71] outline the state-of-the-art knowledge of gas porosity and lack-of-fusion flaws due to melt pool instabilities in PBF processes. Grasso and Colosimo [31] present a defect classification of PBF process-induced defects based on process signatures, to support in-situ monitoring and online defect detection. The present contribution follows defects taxonomies proposed in [31] (and references therein), integrating it with other literature resources (of both non-ontological and ontological nature).

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\(^1\)https://github.com/AndreaMazzullo/DefectOnt
\(^2\)https://www.w3.org/TR/owl2-overview/
\(^3\)https://protege.stanford.edu/
2.2. Ontology-related literature

Given its closely related focus (despite not overlapping with ours, content-wise), we relied on ExtrOnt, an ontology for the description of an extruder components proposed by Ramírez-Durán et al. [61], as a gold standard for the development of our knowledge base, adhering to the authors’ methodological, design, and presentation choices.

With a broader scope, other upper or domain ontologies for AM have been proposed in the literature. The Manufacturing's Semantics Ontology (MASON) [49] is an upper ontology for the conceptualisation of core additive manufacturing domain notions. The US National Institute of Standards and Technology (NIST) propose an ontology for AM, that we label NIST AM [80, 81], to support the development of laser and thermal metamodels. Towards interoperable knowledge and data management in applications, Sanfilippo et al. [66] introduce another ontology for AM (Onto4Additive), based on the upper Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) [13].

Other related AM ontologies include the following (cf. also literature reviews in Sanfilippo et al. [66] and Ramírez-Durán et al. [61]): the Additive Manufacturing Ontology (AMO) [1], based on the upper Basic Formal Ontology (BFO) [3]; the Innovative Capabilities of Additive Manufacturing (ICAM) ontology [34]; a Smart Applications Reference (SAREF) [23] extension for semantic interoperability in the industry and manufacturing domain (SAREF4INMA) [18]; the Semantically Integrated Manufacturing Planning Model (SIMPM) [73]; the Manufacturing Resource Capability Ontology (MaRCO) [37]; the Manufacturing Service Description Language (MSDL) ontology [2]; the Politecnico di Milano–Production Systems Ontology (P-PSO) [28]; the Ontology of Standard for the Exchange of Product model data (OntoSTEP) [8]; the ontologies proposed by Dinar and Rosen [21], Liang [52], Roh et al. [64], and Li et al. [50]. Finally, within the EU-funded project EMMC, the recently proposed European Materials Modelling Ontology (EMMO) [36] provides a standard representational upper (nominalistic) ontology framework based on state-of-the-art knowledge on material modelling and engineering.

3. Ontology design and development

To develop our ontology, we followed the approach proposed by Ramírez-Durán et al. [61], with the adoption of the NeOn Methodology [77] and in particular of the Six-Phase + Merging Phase Waterfall Ontology Network Life Cycle Model. This model, allowing for a flexible interplay between pre-existing ontological and non-ontological resources, consists of the following phases, which will be detailed in the remainder of this section: initiation, reuse, merging, re-engineering, design, implementation, and maintenance.

3.1. Initiation phase

As by the methodological framework of Suárez-Figueroa et al. [76], we initially developed an Ontology Requirements Specification Document (ORSD), summarised in Table 1, with the following goals: defining the purpose and the scope of our ontology; selecting the implementation languages; identifying intended users and uses of the ontology; formulating in natural language groups of competency questions (CQs), to be expressed and answered by our ontology; providing a pre-glossary of terms appearing in the CQs.

To better illustrate the purpose and the intended uses of our ontology, we present the following simplified scenario, involving a MAM production service monitored and regulated by a control system relying, for instance, on a machine learning architecture. Suppose that, during a 3D printing process, the monitoring system detects a feature that is classified (by means of, e.g., a pre-trained convolutional neural network) as a porosity defect, consisting of a void encapsulated within bulk material. Moreover, assume that the system controller (based on, e.g., a reinforcement learning mechanism), in an attempt to mitigate the propagation of the feature, sequentially modifies relevant build chamber parameters, powder handling and deposition system parameters, and the laser scanning speed, observing that only the latter has an impact on limiting the defect. The purpose of our ontology is to formalise the domain knowledge required to infer that the detected porosity is an instance of a process-induced defect, rather than of an equipment-induced one (given that all other possible equipment-related parameters have been ruled out as influences on the feature).
In such contexts, our ontology can be used to: provide a (both machine- and human-readable) structured representation of MAM defects, including their main characteristics and mutual relationships; enrich the online monitoring and troubleshooting capabilities of controllers by means of logic-based reasoning services; improve the user interface to MAM production processes, integrating black-box controller systems with a user-queryable and explainable diagnostic framework.

Finally, we have grouped the CQs along four dimensions, constituting the backbone of our ontology modular structure: (i) MAM-related (CQAm); (ii) spatial-related (CQSp); (iii) measure-related (CQMe); and (iv) sensor-related (CQSe).

3.2. Reuse phase

In order to obtain the domain knowledge required to express and formalise relevant properties of MAM defects, we collect material from both ontological and non-ontological resources. While the latter are based on (not yet formalised) literature on MAM defects, we relied on already existing additive manufacturing ontologies to gather structured knowledge related to MAM processes. The selected ontologies were preferred over other available resources based on the following criteria: (i) possibility of integrating class and property hierarchies with other non-ontological resources; and (ii) vocabularies capable of expressing properties of defects determined by the CQs. In the following, we present the relevant material divided along the four dimensions determined by the groups of CQs.

MAM-related resources

As our main non-ontological resources related to MAM defects, we identify: Grasso and Colosimo [31], providing a classification that relates each kind of defect with the main causes analysed in the literature; Malekipour and El-Mounayri [53], similar to the previous article in scope and purpose, but providing a different taxonomy of defects; Snow et al. [71], focusing mainly on the MAM domain, while maintaining a neutral and interoperable environment, we use instead the following ontologies: NIST AM [81]4; and Onto4additive [66]5. Finally, as a methodological guidance and as a source for specific module development (cf. Measure-related resources), we rely on the ExtruOnt ontology [61]6.

Spatial-related resources

To model spatial-related, geometrical or topological, concepts and relations, we choose GeoSPARQL 1.1 [15]7. Additional spatial-related concepts are inherited from the MASON [49]8 ontology.

Measure-related resources

To express metrological features in our ontology, we rely directly on the OM4ExtraOnt module developed by Ramírez-Durán et al. [61]. This module is obtained by removing all the classes and properties not relevant to the manufacturing setting from the OM ontology [63]9.

Sensor-related resources

As main ontological resource to conceptualise observation- and sensor-related notions, we select the Semantic Sensor Network (SSN) ontology [35]10.

3.3. Merging phase

With the aim of improving semantic interoperability and knowledge exchange in applications, we structure the upper or domain ontologies identified in the reuse phase so to be aligned with the DefectOnt framework. In order to merge these ontologies, we perform the following steps.

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4https://github.com/iassouroko/AMontology.
5https://ontohub.org/repositories/additive-manufacturing.
6http://siul02.si.ehu.es/bdi/ontologies/ExtruOnt/docs/.
7https://opengeospatial.github.io/ogc-geosparql/geosparql11/index.html.
8https://sourceforge.net/projects/mason-onto/.
9https://github.com/HajoRijgersberg/OM.
10https://www.w3.org/TR/vocab-ssn/.
| Purpose | Representation of and reasoning about defects and defect sources in MAM processes, enhancing inference-based diagnostic capabilities to support the user in production control and decision making phases. |
|---|---|
| Scope | Diagnosis and troubleshooting in MAM machines and processes. Potential application contexts are research laboratories and industrial settings. |
| Implementation languages | OWL 2 (description logic syntax). |
| Intended users | Domain experts, product designers, company employees. |
| Intended uses | • Aid user understanding of the classification of MAM defects and corresponding sources. • Enhance automated MAM process control systems with high-level reasoning capabilities. • Guide user interaction with automated MAM process control systems by means of ontology-based explainable diagnostic services. |
| Ontology requirements | • Non-functional requirements: Ontology based on defect classifications from state-of-the-art surveys in the MAM literature. • Functional requirements: Groups of competency questions (CQs). |
| CQAm MAM-related CQs | CQAm.1 Is the feature $d$ an instance of a porosity defect? CQAm.2 Is defect $d$ induced by a process parameter? CQAm.3 . . . |
| CQSp Spatial-related CQs | CQSp.1 Is the MAM product $pr$ affected by any equipment-induced surface defects? CQSp.2 Are there balling defects located on the surface layers of product $pr$? CQSp.3 . . . |
| CQMe Measure-related CQs | CQMe.1 What is the melt pool temperature in degrees Celsius? CQMe.2 What is the thickness in millimetres of layer $l$? CQMe.3 What is the length in metres of the cracking defect instance $d$? CQMe.4 . . . |
| CQSe Sensor-related CQs | CQSe.1 Which sensors are hosted by platform $pl$? CQSe.2 Does any sensor hosted by platform $pl$ observe an instance of a porosity defect? CQSe.3 . . . |
| Pre-glossary of terms | Defect, porosity, cracking, balling, equipment-induced defect, process-induced defect, product, layer, sensor, platform, melt pool, . . . |
(i) We select higher-level classes (with respect to our defect-related concepts) to be introduced in the DefectOnt hierarchy (e.g., Entity from MASON ontology, Abstract, Physical, Characteristic from NIST AM ontology, PhysicalObject from Onto4Additive ontology, SpatialObject from GeoSPARQL ontology, Property from SSN ontology).

(ii) We identify classes that (for our modelling purposes) formalise interchangeable notions, in order to set them as equivalent in the class hierarchy of the DefectOnt ontology (e.g., PhysicalObject from the Onto4Additive and SpatialObject from the GeoSPARQL; Characteristic from NIST and Property from SSN).

(iii) We devise class sub-hierarchies to connect the vocabulary and the axioms from different ontologies (e.g. Characteristic from NIST and ObservableCharacteristic from SSN introduced as subclass; Physical from NIST and SpatialObject from GeoSPARQL introduced as subclass).

3.4. Re-engineering phase
As already mentioned, our main non-ontological resources identified in the reuse phase are Grasso and Colosimo [31] (in particular, Table 1 and references therein), Snow et al. [71], and Malekipour and El-Mounayri [53]. These references are used to extract a conceptual framework based on defect types and corresponding sources, compatible with the purpose, the intended uses, and the implementation languages of the DefectOnt ontology.

3.5. Design phase
To facilitate development, interoperability, and maintenance (in line with the approach by Ramírez-Durán et al. [61]), our DefectOnt ontology is based on a modular structure, reflecting the dimensions that emerge with the ORSD development in the initiation phase. The DefectOnt ontology consists of the following three modules.

1. MAM4DefectOnt, a MAM-related module importing the following ontologies:
   1.1 NIST4DefectOnt, a module obtained from the NIST AM ontology;
   1.2 ONTO4ADD4DefectOnt, derived from the Onto4Additive ontology;
   1.3 Spatial4DefectOnt, to represent spatial-related notions, in turn consisting of the following modules:
      1.3.1 GeoSPARQL4DefectOnt, obtained from the GeoSPARQL1.1 ontology;
      1.3.2 MASON4DefectOnt, derived from the MASON ontology.

2. Measure4DefectOnt, a measuring-related module importing OM4ExtruOnt, a submodule originally developed for the ExtruOnt ontology from the OM ontology.

3. Sensor4DefectOnt, a sensor-related module consisting of the submodule SSN4DefectOnt obtained from the SSN ontology.

To design our ontology modules, we perform the following main steps:

(i) In a preliminary class hierarchy of the MAM4DefectOnt module, we structure the domain knowledge formalised from the non-ontological resources during the re-engineering phase (e.g., by introducing the Defect class and related sub-classes).

(ii) We prune the class hierarchies of the ontologies selected in the re-use phase, maintaining only the most relevant vocabulary and axioms, to obtain the submodules for MAM4DefectOnt, as well as for its submodule Spatial4DefectOnt, Measure4DefectOnt, and Sensor4DefectOnt.
We refine the ontology formalisation of Step (i) by adding to the MAM4DefectOnt module axioms based on classes and properties from submodules devised in Step (ii) (e.g., Defect-related axioms based on the influencedBy property from NIST ontology).

We enrich the class hierarchies of Step (ii) submodules to further improve the ontology formalisation process (e.g., introducing in Spatial4DefectOnt the class Ball as subclass of Geometric_entity from MASON ontology).

We modify class hierarchies and axioms from the submodules obtained in Step (ii) to adhere to the non-ontological resource formalisation performed in Steps (i) and (iii) (e.g., by setting EquipmentParameter as a sibling class of ProcessParameter, rather than subclass (as in NIST), in accordance with Grasso and Colosimo [31]).

We perform a terminological normalisation process, to align the naming scheme for short IRIs of DefectOnt classes (e.g., by changing influencedBy from NIST to isInfluencedBy; Geometry_entity from MASON to GeometricEntity).

### 3.6. Implementation phase

Initially partly expressed by means of a description logic (DL) language [6], our ontology is fully implemented in OWL 2, using the Protégé ontology editor. According to the Protégé ontology metrics, DefectOnt can be expressed with the logical constructs provided by the \( \mathcal{ALC} \mathcal{H} \mathcal{O} \mathcal{T} \mathcal{Q}(\mathcal{D}) \) DL language.

### 3.7. Maintenance phase

As a time-consuming and error-prone task, the knowledge extraction process for the design of the DefectOnt ontology comes with a (still active) maintenance protocol. As prescribed by the selected Ontology Network Life Cycle Model, whenever a modelling error is detected, our ontology re-enters one among the reuse, merging, re-engineering, or design phases for corrections.

### 4. Ontology modules

Along the dimensions identified in the ontology development process (cf. Section 3) and depicted in Figure 1, the DefectOnt modules provide relevant vocabulary and formalise the domain knowledge required to represent the main features of production defects possibly occurring in MAM processes. We illustrate them in detail in the rest of this section, using DL syntax [6] for the OWL 2 axioms here presented.

#### 4.1. MAM4DefectOnt Module

The MAM4DefectOnt module is the primary module of DefectOnt ontology. This module consists of three submodules: (1) NIST4DefectOnt, (2) ONTO4ADD4DefectOnt, and (3) Spatial4DefectOnt. Modules (1) and (2) are obtained from the NIST AM ontology and the Onto4Additive ontology, respectively. Module (3) in turn consists of the following submodules: GeoSPARQL4DefectOnt, derived from GeoSPARQL1.1, and MASON4DefectOnt, from the MASON ontology. In the following we present and discuss the relevant axioms of the MAM4DefectOnt module, focusing on the representation of the different types and sources of MAM defects analysed in the literature.

##### 4.1.1. Defect types in MAM4DefectOnt

The main class of the module used to represent the different kinds of MAM defects studied in the literature is the Defect class (cf. Figure 2). On this class, we first impose the following constraint:

\[
\text{Defect} \sqsubseteq \text{PhysicalObject} \sqcap \exists \text{affects} (\text{PhysicalArtefact} \sqcup \text{Material}),
\]

where: PhysicalObject, PhysicalArtefact, and Material are classes in ONTO4ADD4DefectOnt; affects is a newly introduced object property, used to represent the relationship between a defect and a physical entity
that is affected by it, having domain Defect, range Physical (from the NIST4DefectOnt module), and inverse property isAffectedBy.

As a further step, we leverage the Spatial4DefectOnt module imported by MAM4DefectOnt to provide a location-based classification of defects. First, we define a located defect as a defect that overlaps with some region of an AM layer, as follows:

\[
\text{LocatedDefect} \equiv \text{Defect} \sqcap \exists \text{sfOverlaps.AMLayerRegion},
\]

where: \text{sfOverlaps} comes from the Spatial4DefectOnt submodule, in turn obtained from GeoSPARQL1.1, where it represents the partially overlapping relation from the region connection calculus (RCC) [62]; and \text{AMLayerRegion} is a newly introduced subclass of \text{PhysicalRegion}, in turn set in MAM4DefectOnt as subclass of PhysicalObject from ONTO4ADD4DefectOnt. Moreover, we distinguish between internal defects (i.e., defects located in overlapping with some infill regions, and with infill regions only, of an AM layer) and surface defects (i.e., defects located so to overlap with contour regions of an AM layer). The axioms formalising the above characterisation are the following:

\[
\text{InternalDefect} \equiv \text{LocatedDefect} \sqcap \exists \text{sfOverlaps.InfillRegion} \sqcap \forall \text{sfOverlaps.InfillRegion},
\]

\[
\text{SurfaceDefect} \equiv \text{LocatedDefect} \sqcap \exists \text{sfOverlaps.ContourRegion},
\]

together with the axioms stating that ContourRegion and InfillRegion, together with PowderRegion, are disjoint subclasses of AMLayerRegion, and AMLayer \subseteq \text{hasPart}.AMLayerRegion.

To formalise additional domain knowledge on MAM defects, we rely on the MAM defect classification proposed by Grasso and Colosimo in [31]. Due to its level of detail, this classification is preferred as the main reference framework over others in the AM literature (e.g., [20, 26, 70]). However, aiming at a broad and consistent representation model for MAM defects, we integrate in our ontology also other resources from the literature, adjusting where needed the overall structure of Grasso and Colosimo classification (cf. section 3).

In [31], the MAM defects are organised in six main categories, represented in our module by corresponding subclasses of the Defect class: (i) porosity (PorosityDefect); (ii) balling (BallingDefect); (iii) geometric defects (GeometricDefect); (iv) surface defects (SurfaceRoughnessDefect); (v) cracks and delaminations (CrackingDefect); (vi) microstructural inhomogeneities and impurities (MicrostructuralDefect). We introduce
the SurfaceDefect and InternalDefect class to model purely location-based notions of defects, with respect to the AM layers they overlap with. Therefore, we employ the class SurfaceRoughnessDefect to represent the specific kind of surface defects affecting the roughness of a product surface, that Grasso and Colosimo simply refer to as surface defects.

In order to present the ontology axioms used to connect these classes of defects with their corresponding sources, as well as to formalise their relationships with other AM concepts, we report in the following the main features of each group of defects.

**Balling defects.** The surface tension generated in the melt pool can lead to melted balls of liquid metal that solidify into spherical particles, generating the so-called balling phenomenon. These small spheres of metal may affect both the internal layers of the product, as well as its surface, influencing the component surface roughness and porosity, and (if the phenomenon is very pronounced) it may eventually lead to (hemispherical) protrusion on the solidified structure. Balling can have dramatic effects on part quality and fatigue life of the component [53]. To translate the above description into logical axioms, we distinguish between InternalBallingDefect and SurfaceBallingDefect as subclasses covering the BallingDefect class, as follows:

\[
\begin{align*}
\text{InternalBallingDefect} & \equiv \text{InternalDefect} \sqcap \\
& \exists \text{isConsequenceOf}.\text{SurfaceTensionPhenomenon} \sqcap \\
& \exists \text{isMadeOf}.(\text{Material} \sqcap \exists \text{hasMaterialState}.\{\text{solidState}\}) \sqcap \\
& \exists \text{hasApproximateGeometry}.\text{Ball}, \quad (5) \\
\text{SurfaceBallingDefect} & \equiv \text{SurfaceDefect} \sqcap \\
& \exists \text{isConsequenceOf}.\text{SurfaceTensionPhenomenon} \sqcap \\
& \exists \text{isMadeOf}.(\text{Material} \sqcap \exists \text{hasMaterialState}.\{\text{solidState}\}) \sqcap \\
& \exists \text{hasApproximateGeometry}.\text{HemiBall}, \quad (6) \\
\text{BallingDefect} & \equiv \text{InternalBallingDefect} \sqcup \text{SurfaceBallingDefect}, \quad (7)
\end{align*}
\]

where: isConsequenceOf is a property introduced in our MAM4DefectOnt module; the property hasApproximateGeometry, as well as the classes Ball and HemiBall, are introduced in Spatial4DefectOnt; SurfaceTensionPhenomenon is set in MAM4DefectOnt as a subclass of Phenomenon, in turn inherited from the
Cracking and delamination defects. According to [20] there are three main cracking mechanisms observed in MAM: (i) solidification cracking along the boundaries, (ii) liquation cracking occurring either in the mushy region or in the partially melted zone, and (iii) delamination, consisting in the separation of two consecutive printed layers. All the three types of cracking are related to the high residual stresses induced by the process [56] as a consequence of stress relief through fracture. This characterising feature of cracking defects is formalised in our ontology as follows:

\[
\text{CrackingDefect} \equiv \text{Defect} \land \exists \text{affects.}\left(\text{AMProduct} \land \exists \text{hasFeature.}\left(\exists \text{isConsequenceOf.}\text{Fracture}\right)\right)
\]

with: \text{hasFeature} object property of \text{ONTO4ADD4DefectOnt}; and class \text{Fracture} introduced in \text{MAM4DefectOnt} within the subclass hierarchy of \text{Phenomenon} from \text{NIST4DefectOnt}. In our module, we also introduce specific subclasses for each type of cracking, in order to better specialise their relationship with the process, namely: \text{SolidificationCrackingDefect}, \text{LiquationCrackingDefect}, and \text{DelaminationCrackingDefect}.

Geometric defects. This class of defects includes all the different kinds of dimensional and geometric deviations from the original, as-designed geometry [53]. In fact, it is widely documented in the literature that complex, lattice, and slender 3D printed structures present non negligible geometric deviation from the the actual, as-build structure and the as-design geometry as generated within Computer Aided Design (CAD) environments [45, 12, 44]. Such kind of defects is defined in the \text{MAM4DefectOnt} module, as follows:

\[
\text{GeometricDefect} \equiv \text{Defect} \land \exists \text{affects.}\left(\text{AMProduct} \land \exists \text{hasGeometry.}\left(\exists \text{hasSignedDeviationFrom.}\text{AsDesignedGeometry}\right)\right),
\]

where: \text{hasGeometry} and \text{hasSignedDeviationFrom} are properties, and \text{AsBuiltGeometry} and \text{AsDesignedGeometry} are classes introduced in the \text{Spatial4DefectOnt} module.

The most common effects leading to geometric defects are: (i) shrinkage, (ii) warping, (iii) curling, and (iv) formation of super-elevated edges. They are inserted into the module as subclasses of \text{GeometricDefect} and defined as: \text{ShrinkageGeometricDefect}, \text{WarpingGeometricDefect}, \text{CurlingGeometricDefect}, \text{SuperelevatedEdgesGeometricDefect}, respectively.

Microstructural defects. Several different classifications can be found in MAM literature to label and classify the defects related to the microstructure of 3D printed components [57, 72]. For our purposes, to provide an axiom characterising microstructural defects, we first introduce in \text{MAM4DefectOnt} the class \text{InhomogeneousMicrostructure} as a subclass of \text{Microstructure}, that we inherit from the NIST ontology. The axiom formalising that a microstructural defect is any defect that affects an AM product with inhomogeneous microstructure is then written as follows:

\[
\text{MicrostructuralDefect} \equiv \text{Defect} \land \exists \text{affects.}\left(\text{AMProduct} \land \exists \text{presents.}\text{InhomogeneousMicrostructure}\right)
\]

where \text{presents} is a newly introduced object property in \text{MAM4DefectOnt}, used to relate physical objects with the characteristics they exhibit. Finally, following Sharratt [69], we distinguish between three types of inhomogeneities of the microstructure that occur during MAM processes, introducing them as corresponding subclasses of \text{MicrostructuralDefect}: (i) impurities (\text{ImpuritiesMicrostructuralDefect}), (ii) grain size characteristics (\text{GrainSizesMicrostructuralDefect}), and (iii) crystallographic textures (\text{CrystallographicTexturesMicrostructuralDefect}).
**Porosity defects.** Fully dense (99.95%) MAM parts can be produced when printing large bulk material components. However, more often a functional design and/or lightweight structures (e.g., lattice) are present in MAM products (cf. Figure 3). In this case porosity—due, e.g., to lack-of-fusion or keyhole effects—can severely affect the performances of 3D printed components. Based on the location of the defects, we further specify the notions of internal and surface porosity defects (cf. Figure 3a and 3b, respectively), formalising them respectively as InternalPorosityDefect and SurfacePorosityDefect, as follows:

\[
\text{InternalPorosityDefect} \equiv \text{InternalDefect} \sqcap \text{VoidRegion} \sqcap \exists \text{hasBoundary}.\text{ClosedSurface} \quad (11)
\]

\[
\text{SurfacePorosityDefect} \equiv \text{SurfaceDefect} \sqcap \text{VoidRegion} \quad (12)
\]

\[
\text{PorosityDefect} \equiv \text{SurfacePorosityDefect} \sqcup \text{InternalPorosityDefect} \quad (13)
\]

where: isBoundaryOf and ClosedSurface are, respectively, a property and a class introduced in Spatial4DefectOnt; VoidRegion is a newly introduced class (cyclically) defined in MAM4DefectOnt as VoidRegion \( \equiv \text{PhysicalObject} \sqcap \forall \text{hasPart}.\text{VoidRegion} \).

Figure 3: View by micro-Computed Tomography showing different kinds of pores in a Stainless Steel 316L 3D printed specimen [16].

**Surface roughness defects.** Surface roughness defects are clearly related to the notion of surface roughness, i.e., to a deviation of the surface texture with respect to an ideal surface plane. In MAM processes, surface roughness is influenced by two main effects: the stair-stepping effects, due to the layer-by-layer nature of the process, and the actual roughness of the metal surface [25, 75]. Additionally, the relative position of the surface strongly influences its roughness, e.g., downward surfaces present much higher roughness than upward surfaces. We formalise the connection between surface roughness defects and the rough surface texture of a product, as follows:

\[
\text{SurfaceRoughnessDefect} \equiv \text{SurfaceDefect} \sqcap \exists \text{affects}.(\text{AMProduct} \sqcap \exists \text{presents}.\text{RoughSurfaceTexture}) \quad (14)
\]

where: AMProduct is a class from the ONTO4ADD4DefectOnt module; and RoughSurfaceTexture is introduced as subclass of SurfaceTexture in MAM4DefectOnt.

4.1.2. Defect sources in MAM4DefectOnt

In order to establish logical connections between MAM defects and their causes, a further classification of defects based on the corresponding sources is required. To this goal, we introduce InducedDefect as a subclass of Defect, defining it as follows:

\[
\text{InducedDefect} \equiv \text{Defect} \sqcap \exists \text{InducedBy}.(\text{Characteristic} \sqcup \text{Material} \sqcup \text{Phenomenon} \sqcup \text{PhysicalObject} \sqcup \text{Process}) \quad (15)
\]
where the newly introduced object property `isInducedBy` represents the relationship between defects and those MAM entities that are known to have an influence on them. According to the classification proposed by Grasso and Colosimo [31], Table 1 (and references therein), that we further extend and specify, MAM defect sources are classified into four main groups, for which we introduce a corresponding subclass of `InducedDefect`: (i) design for additive choices (`DesignInducedDefect`); (ii) equipment (`EquipmentInducedDefect`); (iii) feedstock material (`FeedstockMaterialInducedDefect`); and (iv) process (`ProcessInducedDefect`). In the following, we discuss the axioms that characterise each of the `InducedDefect` subclasses.

**Design-induced defects.** A wrong support design and/or part orientation during the building process can have a dramatic impact on the part quality and performances of 3D printed components. In fact, these two parameters directly influence (i) dimensional accuracy, (ii) surface roughness, and (iii) part microstructure [41, 24, 84, 75]. Accordingly, in the `MAM4DefectOnt` module the class `DesignInducedDefect` includes two other classes, `SupportsInducedDefect` and `OrientationInducedDefect`, defined by the following axioms:

\[
\text{SupportsInducedDefect} \equiv \text{DesignInducedDefect} \cap \exists \text{isInducedBy}.\text{AMSupportStructure} \quad (16)
\]

\[
\text{OrientationInducedDefect} \equiv \text{DesignInducedDefect} \cap \exists \text{isInducedBy}.\text{ProductOrientation} \quad (17)
\]

where `AMSupportStructure` comes from `ONT04DD4DefectOnt`, while `ProductOrientation` is a new subclass of `ProductCharacteristic` introduced in `MAM4DefectOnt`.

**Equipment-induced defects.** Improper or sub-optimal setting and calibration of the MAM equipment can generate several types of defects. This category includes four main sources of defects: (i) beam scanning and deflection system; (ii) powder handling and deposition system; (iii) insufficient baseplate thickness; and (iv) build chamber environmental control (e.g., preheating of the powder bed) [24, 41, 59, 74]. Each of these sources can be linked to different types of defects. For instance, an erroneous calibration of the beam scanning can lead to longer exposure time distorting the melt pool morphology, which directly affects residual stresses, geometric accuracy, and porosity (lack of fusion defects) in the final component [82, 55, 79, 17]. In the `MAM4DefectOnt` module, we introduce the class `EquipmentInducedDefect` that, in accordance with the observations above, includes four subclasses: `BaseplateInducedDefect`, `BeamScanningDeflectionSystemInducedDefect`, `BuildChamberEnvironmentalControlInducedDefect`, and `PowderHandlingDeposition-
SystemInducedDefect. In turn, these are defined by the following axioms:

\[
\text{EquipmentInducedDefect} \equiv \text{InducedDefect} \sqcap \exists \text{isInducedBy}. (\text{EquipmentParameter} \sqcup \text{MfgDevice} \sqcup (\text{Material} \sqcap \exists \text{makes}. \text{MfgDevice}))
\]

(18)

\[
\text{BaseplateInducedDefect} \equiv \text{EquipmentInducedDefect} \sqcap \exists \text{isInducedBy}. (\text{BaseplateMaterial} \sqcup \text{BaseplatePreHeatingTemperature} \sqcup \text{BaseplateThickness})
\]

(19)

\[
\text{BeamScanningDeflectionSystemInducedDefect} \equiv \text{EquipmentInducedDefect} \sqcap \exists \text{isInducedBy}. \text{OpticalParameter}
\]

(20)

\[
\text{BuildChamberEnvironmentalControlInducedDefect} \equiv \text{EquipmentInducedDefect} \sqcap \exists \text{isInducedBy}. \text{BuildChamberParameter}
\]

(21)

\[
\text{PowderHandlingDepositionSystemInducedDefect} \equiv \text{EquipmentInducedDefect} \sqcap \exists \text{isInducedBy}. (\text{MaterialDepositionSystem} \sqcap \exists \text{isAffectedBy}. (\text{ByproductMaterialEjectionInducedDefect} \sqcup \text{SuperelevatedEdgesGeometricDefect}))
\]

(22)

It might be noted that defects induced by the powder handling and deposition system (PowderHandlingDepositionSystemInducedDefect) are not influenced by recoating system characteristics (e.g., the wear of the recoater). In fact, most of the time the recoating system is not the direct source of these defects [41, 24]. Instead, they are generated by the linear motion of the recoater that propagates inhomogeneities present on the powder bed (due to, e.g., super-elevated edges and spatters) along its moving direction.

Feedstock material-induced defects. Powder quality, i.e., powder morphology, directly influences the quality (geometrical accuracy, porosity, and microstructure) as well as the performances (fatigue life) of the component [65, 19, 78, 58]. Another important feature of the powder is its flowability (powder fluidity), which depends on the particle size. If the powder particles are too small or too big, a smooth layer deposition cannot be achieved, eventually even stopping the process. Moreover, uniform powder deposition, smooth deposited powder layer, and uniform spreading, affect surface quality [53, 68]. Based on the observations above, we define the class FeedstockMaterialInducedDefect by means of the following axiom:

\[
\text{FeedstockMaterialInducedDefect} \equiv \text{InducedDefect} \sqcap \exists \text{isInducedBy}. (\text{PackingDensity} \sqcup \text{PowderSizeDistribution})
\]

(23)

Process-induced defects. Process parameters (e.g., laser power, scan speed, and hatch distance) influence the energy density that is introduced into the powder bed domain [39]. The energy density has been demonstrated to control the melt pool morphology and the cooling rate, thus ultimately influencing material microstructure [51], geometric accuracy [83], as well as the porosity of final components [57]. Therefore, we include in the MAM4DefectOnt module the class ProcessInducedDefect, together with the two subclasses
ByproductsAndMaterialEjectionInducedDefect and ParameterAndScanStartegyInducedDefect defined as follows:

\[
\text{ProcessInducedDefect} \equiv \text{InducedDefect} \sqcap \exists \text{isInducedBy}.(\text{Process} \sqcup \text{ProcessParameter})
\]  

(24)

\[
\text{ByproductMaterialEjectionInducedDefect} \equiv \text{InducedDefect} \sqcap \exists \text{isInducedBy}.\text{Ejection}
\]  

(25)

\[
\text{ParameterScanStrategyInducedDefect} \equiv \text{InducedDefect} \sqcap \exists \text{isInducedBy}.(\text{HatchingDistance} \sqcup \text{HeatSourcePower} \sqcup \text{LayerThickness} \sqcup \text{ScanningSpeed})
\]  

(26)

4.1.3. Relating defects types and sources in MAM4DefectOnt

Following Grasso and Colosimo [31], Table 1 (and references therein), in this section we discuss the mappings connecting each type of MAM defects formalised in Section 4.1.1 with the corresponding causes identified in the literature, and modelled in terms of InducedDefect subclasses in Section 4.1.2. Such mappings consist of subsumption axioms of the form \( A \sqsubseteq C \) where: \( A \) is any of the classes BallingDefect, CrackingDefect, GeometricDefect, MicrostructuralDefect, PorosityDefect, SurfaceRoughnessDefect; and \( C \) is the union of subclasses of InducedDefect. These axioms express the fact that defects of type \( A \) are documented in the literature to be caused by at least one of the MAM features that characterise some disjoints in \( C \).

For instance, it is documented in the literature [31] that porosity defects can be induced by: the beam scanning or deflection system; the build chamber environmental control; the powder handling and deposition system; the process parameters and scan strategies; byproducts and material ejections. Accordingly, we express in MAM4DefectOnt that the class PorosityDefect is included in the union of the following classes: BeamScanningDeflectionSystemInducedDefect, BuildChamberEnvironmentalControlInducedDefect, PowderHandlingDepositionSystemInducedDefect, ParameterScanStrategyInducedDefect, ByproductMaterialEjectionInducedDefect, and FeedstockMaterialInducedDefect.

In the rest of this section, we list the mappings axioms for each of the subclasses of Defect discussed in Section 4.1.1.

**Balling defect sources.**

\[
\begin{align*}
\text{BallingDefect} & \sqsubseteq \text{BuildChamberEnvironmentalControlInducedDefect} \sqcup \\
& \text{ParameterScanStrategyInducedDefect} \sqcup \\
& \text{OrientationInducedDefect}
\end{align*}
\]  

(27)

**Cracking and delamination defect sources.**

\[
\begin{align*}
\text{CrackingDefect} & \sqsubseteq \text{BuildChamberEnvironmentalControlInducedDefect} \sqcup \\
& \text{BaseplateInducedDefect} \sqcup \\
& \text{ParameterScanStrategyInducedDefect} \sqcup \\
& \text{SupportInducedDefect}
\end{align*}
\]  

(28)

**Geometric defect sources.**

\[
\begin{align*}
\text{GeometricDefect} & \sqsubseteq \text{BeamScanningDeflectionSystemInducedDefect} \sqcup \\
& \text{PowderHandlingDepositionSystemInducedDefect} \sqcup \\
& \text{BaseplateInducedDefect} \sqcup \\
& \text{ParameterScanStrategyInducedDefect} \sqcup \\
& \text{SupportInducedDefect} \sqcup \\
& \text{OrientationInducedDefect} \sqcup \\
& \text{FeedstockMaterialInducedDefect}
\end{align*}
\]  

(29)
Microstructural defect sources.

\[
\text{MicrostructuralDefect} \subseteq \text{BuildChamberEnvironmentalControlInducedDefect} \quad \text{PowderHandlingDepositionSystemInducedDefect} \quad \text{ParameterScanStrategyInducedDefect} \quad \text{ByproductMaterialEjectionInducedDefect} \quad \text{OrientationInducedDefect} \quad \text{FeedstockMaterialInducedDefect}
\]  

Porosity defect sources.

\[
\text{PorosityDefect} \subseteq \text{BeamScanningDeflectionSystemInducedDefect} \quad \text{BuildChamberEnvironmentalControlInducedDefect} \quad \text{PowderHandlingDepositionSystemInducedDefect} \quad \text{ParameterScanStrategyInducedDefect} \quad \text{ByproductMaterialEjectionInducedDefect} \quad \text{FeedstockMaterialInducedDefect}
\]

Surface roughness defect sources.

\[
\text{SurfaceRoughnessDefect} \subseteq \text{PowderHandlingDepositionSystemInducedDefect} \quad \text{ParameterScanStrategyInducedDefect} \quad \text{SupportInducedDefect} \quad \text{OrientationInducedDefect} \quad \text{FeedstockMaterialInducedDefect}
\]

4.1.4. Competency questions for MAM4DefectOnt

The MAM4DefectOnt module, together with its Spatial4DefectOnt submodule, allow us to answer, for instance, to the following CQs:

CQAm.2 Is the feature \(d\) an instance of a porosity defect?

CQSp.2 What is the length in metres of the cracking defect instance \(d\)?

4.2. Measure4DefectOnt Module

This module is intended to provide axioms, classes, and properties that are necessary to describe AM process and product features requiring notions related to measures, measuring units, and scales. Relevant classes (e.g., Temperature, CelsiusTemperature, Area, Length) are included in its only submodule, OM4ExtruOnt, which is imported from the ExtruOnt [61] by leveraging the modular structures of both ExtruOnt and DefectOnt ontologies. Ramírez-Durán et al. obtain this submodule from the OM ontology via a pruning process that retains only those concepts and properties pertaining to manufacturing process and components. In particular, this module is intended to provide the necessary knowledge to address, for instance, the following competency question:

CQMe.3 What is the length in meters of the cracking defect instance \(d\)?
4.3. Sensor4DefectOnt Module

This module is intended to enable domain experts and/or online defect detection systems to gain insights from data measured by means of sensors installed on the AM machine. In particular, the axioms of the class FeatureOfInterest together with its related properties and subclasses are present in this module through the submodule of the SSN ontology, SSN4DefectOnt. Moreover, this module provides useful concepts to evaluate the quality of MAM processes allowing to potentially perform online defect diagnosis and troubleshooting. In particular, sensor4DefectOnt allows to answer the following competency questions:

CQSe.2 Does any sensor hosted by platform pl observe an instance of a porosity defect?

5. Conclusion

In the present contribution, we have introduced an OWL 2 ontology to represent MAM defects, together with their constituting features and sources. Our ontology aims at filling a gap in the literature on AM knowledge bases, providing dedicated vocabulary and axioms to capture specific defect-related domain knowledge. To provide additional expressivity and modelling capabilities, we have also integrated our ontology with several upper-level ontologies, as well as domain-specific ontologies from different domains.

As future steps, we plan to extend DefectOnt with the capability of relating defects with measured quantities coming from either in-situ or ex-situ measurements. Moreover, we are interested in improving the alignment of DefectOnt with upper ontology or domain-specific knowledge bases from the AM literature. In a similar direction, to foster the integration of heterogeneous data sources, we plan to consider ontology-based data access techniques and frameworks, focusing in particular on the OWL 2 QL Profile [43]. Finally, we are interested in investigating the addition of a temporal dimension to our ontology, for temporal data modelling and predictive analysis [4, 5, 14, 38]

Our long term goal is to use these additional representation and reasoning features to mitigate manufacturing defects, by automatically adjusting those process parameters that are found to be related with the corresponding defect sources. Indeed, our defect ontology is meant to pave the way towards real-time control systems for MAM processes. In fact, combining machine learning mechanisms with knowledge-based representation and high-level reasoning techniques, it can potentially lead to a self-adaptive system able to perform online diagnosis and troubleshooting.

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