Ontological modelling of welding processes

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Abstract: In this work, an ontological model for welding processes is proposed and the need to manage the information and knowledge associated with such complex discipline is justified. First, an overview of the meaning and use of the models for this purpose and the concept of interoperability applied to the information contained in the welding standards is given. Next, an approach to the concept of ontology is made, the ontology applications for engineering, basic functionalities of ontologies and the way in which they are implemented. The work concludes showing some entities of the proposed ontology, focusing on the definition and classification of welding processes and knowledge inference based on the information contained in the ontology.

Keywords: Ontological modelling, Interoperability, Welding, Standardization.

1. Introduction

The objective of this work is to show the need of effectively manage knowledge about welding processes, particularly the one related to their specification; an issue addressed in standards and on whose correct definition and consistency largely depends on the adequate transmission and sharing of information related to welding.

Models are simplifications of reality that facilitate its understanding or the study of a part or a feature of it. Modelling in welding allows to simplify and synthesize the information associated with such complex field which, seen from the perspective of standardization, addresses multiple variants, diverse technical facets and quality and safety requirements, generating a huge amount of information. Complex and knowledge intensive activities such as design, planning, execution and control of welding operations are also the subject of different standardization initiatives. All above activities are part of the life cycle of many products; therefore, their management, including the associated knowledge is a requirement of current manufacturing systems, characterized by integration and interoperability [1,2].

NIST Internal Report 7289 [3] addresses interoperability needs, understood as the ability to exchange information and knowledge, and the role of standardization in this matter. Also in this direction is PSL initiative [4], whose objective is the creation of a high-level neutral language for the specification of processes and the integration of multiple applications related to processes throughout the product life cycle. This standard has been the basis for the development of an ontology focused on the specification of processes and that responds to the needs of discrete manufacturing processes, such as welding.

In following sections, an approach to the concept of explicit or implemented ontology and its applications in engineering are made; after, an ontological model that facilitates semantic interpretation of the terms present in welding processes standards are introduced.
2. Ontologies. Overview and implementation

Among the possible alternatives for knowledge representation and management stands up the use of ontologies. A solution present in various manufacturing engineering applications [5-7], although still very little extended in the field of welding.

Ontologies establish the bases that organize and guide the knowledge of reality through its properties, principles and causes. An ontology accurately and unambiguously identifies and describes the concepts, classes, entities, or terms in its domain of interest, as well as the valid relationships between them, and provides formal definitions and axioms that restrict its interpretation. In this sense, ontologies are the technological key to describe the semantics of information, allowing its exchange and overcoming the problem of implicit and lost knowledge [8].

The purpose of ontologies is to make it easier for humans and machines to share certain common knowledge in a structured way. For this, all the participants in the domain must share the set of terms and definitions of an ontology that represent the entities, whose correct interpretation is needed for communication in a given domain [9].

The following definition of ontology is according to the above. An ontology is a formal description of the entities within a given domain: the properties they possess, the relationships they participate in, the constraints they are subject to, and the patterns of behaviour they exhibit [10].

Therefore, in an ontology for a specific welding domain, its entities represent everything that serves to describe and specify this domain, such as the welded materials and the filler materials, or the welding processes and their variables. Properties of these entities represent, for instance, the characteristics of the welding processes or those of the welded joints. Relationships entities participate in can serve, for instance, to establish the types of consumables and the protection means used in a certain welding process. Entities constraints can establish, for instance, the scope covered by a certain welding process that differentiates it from other processes. Finally, an example of the behaviour exhibited by an entity belonging to the welding domain could be the shape of the weld bead and the presence or absence of certain defects in the welded part.

In the previous paragraph, the terms that appear in the definition of ontology have been interpreted using examples from the welding domain. The correct interpretation and application of these concepts allows to define an ontological model that facilitates communication and information exchange in this domain. However, an ontology goes beyond an effective and efficient means of transmitting information. An ontology allows capture knowledge in a domain of interest, and although in its practical applications in engineering this means the storage and maintenance of data, ontologies are located at a higher level than information systems, since in addition they allow reasoning based on the information they contain. Furthermore, the captured knowledge can be shared and reused for various purposes and applications related to its domain.

To achieve these purposes, both those related to the transmission of information and those related to knowledge management, it is necessary to formalize and implement the ontology. This implementation is done using specific languages and, usually, with the help of ontology editors.

OWL (Ontology Web Language), developed by the W3C (World Wide Web Consortium), is one of the most widely used ontological languages. OWL is a language conceived for publishing and share data on the Web using ontologies, and for using in applications that process the content of information, since it provides a formal semantics that can be computer interpretable [11].

With the help of editors such as Protégé it is possible to build domain ontologies through the definition of classes, class hierarchies, properties, restrictions for the value of properties, relationships between classes, and properties of these relationships [12]. This ontology editor is based on a logic model that allows the use of reasoners to check consistency in the ontology statements and definitions, and capable to recognize that the concepts fit each of the definitions.

The main functionality of reasoners is the validation and analysis of ontologies [8]. A reasoner checks the ontology to automatically compute the hierarchy of the classification, or asserted hierarchy, and verify its logical consistency. After the check performed by the reasoner, it can be seen if any class is inconsistent or if it has been reclassified, becoming part of another class within the inferred hierarchy.
3. First approach to the ontological model of welding processes

Ontological models are representations of reality based on ontologies. The proposed model, limited to the classification of welding processes and the definition of some related concepts, is written in OWL language and has been implemented using the Protégé ontology editor.

Taxonomy constitutes a basic and essential tool for structuring knowledge in any field of study [13]. The main criteria used for classifying welding processes related to chemical composition similarity of materials to be welded (homogeneous welding and heterogeneous welding), the physical state of these materials during welding (solid state welding, welding, soldering and brazing), and the primary energy source used to carry out the process (electrical, mechanical, thermochemical, etc.).

The application of each of those three criteria to the set of welding processes results in a grouping of them according to their particular characteristics, generating mutually exclusive categories. For instance, a welding process cannot be homogeneous and heterogeneous at the same time and cannot simultaneously belong to two or more of the following categories: Welding, Soldering, Brazing and SolidState (figure 1). However, the three classification criteria considered (similarity of the materials to be welded, physical state during welding and the source of energy used) applies to all welding processes. Hence, the same welding process will belong to a specific group of each of these categories. For instance, a SMAW welding process, using an electrical power source, belongs to Electrical; it is a fusion weld, so it is included in Welding; and it materializes a welded joint that may be homogeneous or heterogeneous, so it may belong to the Homogeneous or Heterogeneous category depending on the case.

![Figure 1. Taxonomy of welding processes.](image)

This taxonomy has served as the basic for a part of the ontology. The ontological model has the five basic classes, or categories, necessary to model the representation of the welding processes: Material, PhysicalState and PrimaryEnergySource, which are associated with the three established classification criteria; ProcessTemperature, which is necessary to differentiate between soldering and brazing; and Process, which all welding processes belong to (figure 2(a)).

In turn, these basic classes, or first level classes of the ontology, are structured giving rise to other subclasses, which constitute a more refined representation or model of reality. Figure 2(b) shows Material class specialization in the BaseMaterial and Filler classes, which serves to differentiate between the materials welded and those used as filler material. These two classes, BaseMaterial and Filler, are not disjoint. Therefore, a material used as a filler –it belongs to the Filler class- can be the basic constituent of a part to be welded in another or in the same welding process –it belongs to the BaseMaterial class-. The difference between disjoint classes and non-disjoint classes is a basic function provided by Protégé ontology editor. However, it is of great importance in modelling, since it transfers essential information to the semantics of the model in order to correctly interpreting the characteristics of a certain welding process.

The developed ontological model has been specialized according also to other needs. For instance, the two classes in which the BaseMaterial class specializes: CooperAlloy and FerrousAlloy (figure 2(b)), could be structured into other classes corresponding to the different types of copper-base alloys,
steels, cast iron, etc. In this way, other classes of base material can be established at the same level as the existing ones, as aluminium and titanium alloys.

Figure 2. Class hierarchy of the ontological model developed in Protégé: (a) first level classes, (b) Material class, and (c) PrimaryEnergySource class.

Figure 2(c) shows welding processes taxonomy according to the type of energy source considered, as well as their structuring at different levels. A taxonomy that can also be refined so that the ontology considers, for instance, the different types of electric arc and resistance welding processes, which would be subclasses of ElectricArc and ElectricResistance respectively.

On the other hand, as can be seen in figure 3(a), the class hierarchy defined, or asserted, corresponding to the Process class is not specialized, since all the processes considered (Brazing, Electrical, ERW, EXW, FerrousAlloyWithSilver, Heterogeneous, Homogeneous, Mechanical, SMAW, Soldering, SolidState, Thermochemical, TW and Welding) appear at the same level. In other words, the asserted hierarchy of classes, which is identified in the upper right part of figure 3(a) by “Asserted”, does not contemplate the semantics associated with processes categories established based on the three criteria previously defined and that have been represented in figure 1.

However, some of these welding process descriptions make use of axioms like those shown in figure 3(c) for the SMAW process. The content of this figure, identified as “Description: SMAW”, has two subsections: “Equivalent To” and “SubClass Of”, corresponding to the two modes provided in the ontology editor to describe a class. In this case, the SMAW class is a subclass of the class defined by the axioms that follow “SubClass Of”.

The meaning of these axioms is below:

"Process", which appears last, indicates that the SMAW class is a type of welding process. That is, a subclass of the Process class.

"HasPrimaryEnergySource some ElectricArc" means that the SMAW class is a subclass of the welding processes that use an electrical power source to perform welding.

"HasMaterial only (Material and hasPhysicalStateDuringProcess some Liquid))" means that the SMAW class is a subclass of welding processes in which only materials of the BaseMaterial or Filler classes participate, and that at some point in time welding process, these materials are in a liquid state.

In short, the SMAW class is a subgroup, a subclass, of the intersection of the three classes defined by the previous axioms. In other words, the axioms described above configure the necessary condition that a welding process must satisfy to belong to the SMAW type. Nevertheless, as these axioms do not configure a sufficient condition, not all the processes that satisfy them belong to the SMAW type.
When an axiom or a group of axioms that describe a class are the necessary and sufficient condition for this class, they appear below “Equivalent To” in the class description box shown in figure 3(c). For instance, this is the case of electrical welding process class, Electrical in the ontology, which is defined by the axiom "HasPrimaryEnergySource some ElectricArc". This means that any welding process that uses an electrical power source to perform welding belongs to Electrical class, and all processes in this class use an electrical power source to perform welding.

After discussing the difference between equivalent to and subclass of as methods for defining classes in the ontology, and example of knowledge inference will be shown. The first two axioms in figure 3(c) correspond to the definitions of the Welding and Electrical classes respectively, which means that any process of type SMAW belongs to these two categories. Something not reflected in the asserted information contained in the class hierarchy of Process class (figure 3(a)), but shown in figure 3(b), identified with "Inferred" in the upper right, which corresponds to the hierarchy of classes inferred by the ontology, or inferred hierarchy.

Inference is one of the basic functionalities of an ontology and makes possible knowledge generation from the asserted information contained in the ontology. For instance, figure 3(b) shows an inferred taxonomy of welding processes that was not been previously asserted. Reasoners are the tools that classify and check consistency information contained in the ontology, enabling the knowledge inference. Reasoners also support queries generation through which the user can retrieve the asserted information and obtain new information and inferred knowledge from the ontology. Other inference examples are shown below.

The mere fact of establishing relationships between the individuals of the ontology implicitly provides inferred knowledge about these individuals. Once the ontology class taxonomy has been defined, we proceed to "populate" the ontology. That is, to introduce individuals into the ontology, such as the welding processes or the base materials to be welded. For this, it is practical to define these individuals as members of the group of entities in the ontology editor identified as "Individual"; using, for instance, the label "M" for materials and the label "P" for welding processes, as can be seen in figure 4(a). Naturally, this does not add any semantic content to the ontology. In fact, if we make a query to the ontology about which individuals belong to the Material or Process classes, the result is null (figure 4(b)). However, as relationships are established between the individuals of the ontology, these relationships give semantic content to the individuals. For instance, the relationship hasMaterial has been defined between individuals of the Process (Domain) and Material (Range) classes as shown in...
Thus, when applying the hasBaseMaterial relationship between the individuals P_1 and M_1 of the ontology (figure 4(d)), the ontology infers that these individuals belong respectively to the Process and Material classes. Which can be verified by repeating the previous query (figure 4(e)).

In summary, this simple example includes two types of knowledge inference: on the one hand, the consideration of individuals in the Process and Material classes, who had not been asserted as such, and who do now appear in figure 4(f) as inferred "Instances" (on a yellow background); and on the other hand, the fact that domain and range, defined in the ontology for hasMaterial are inherited by the hasBaseMaterial relationship, a specialization of this “ObjectProperty” (figure 4(g)); although, as can be seen in (figure 4(h)), domain and range do not form part of hasBaseMaterial description.

Knowledge can also be inferred by rules written in SQWRL (Semantic Query-Enhanced Web Rule Language). For instance, the rule in figure 5(a) infers that for any welding process (?x) of the FerrousHomogeneus class, such as P_3 (figure 5(b)), the base material (?y), which is set as shown in figure 5(c), it will be of type FerrousAlloy, that is showed by the ontology editor on a yellow background (figure 5(d)).

Now we suppose a new assignment of welding processes in which P_3 is of type FerrousHomogeneous (figure 5(b)) and P_2 is of type Heterogeneous (figure 5(e)). However, the answer to the query in figure 5(f), in which the ontology is asked which processes are not homogeneous, indicates that there are no “non-homogeneous” welding processes in the ontology (figure 5(f)). This answer is explained because the reasoning in OWL (with Description Logics) is based on what is known as open world assumption (OWA), or open world reasoning (OWR). OWA means that we cannot assume that something is false because it has not been asserted to be true. In this case, with OWA, the ontology does not infer that P_2 is a non-homogeneous welding process until it is asserted and, an implicit way of asserting that heterogeneous welding processes, such as P_2, are also non-homogeneous would be defining the Homogeneous and Heterogeneous classes as disjoint. After making this statement in the ontology (figure 5(g)), the result of the query will be the one initially expected (figure 5(h)).
4. Conclusions and future work
The definition and classification of welding processes under ontological criteria has an obvious interest in the field of standardization. For instance, applied to the standards whose object is the qualification of welding procedures [14-16]. Indeed, the use of an ontological proposal allows establishing consistent definitions that include the complete semantics of welding processes, facilitating interoperability. In other words, facilitating the correct interpretation, transmission, sharing and reuse of information and knowledge in the welding processes domain.

Below is the list of future works proposed:

- Extend and complete the current ontological proposal. For instance, update one of the classification criteria, which only considers homogeneous and heterogeneous weld unions, to include the weld union category of different materials as stated in the UNE standards [15].
- Evaluate concepts consistency in definitions included in standards related to welding processes [14-17] and verify the semantic equivalence of their terms and definitions in different languages.
- Carry out an ontological description for concepts related to welding whose definition can be confusing due to the intrinsic ambiguity of natural language, and establish equivalences for these concepts among standardization systems [16-19].
- Establish an ontological definition for the categories of welding processes resulting from the classification based on their degree of automation: manual welding, semi-automatic welding, mechanized welding and automatic welding.
- Carry out an ontological definition of welding processes based on the information contained in ASME standards [18].

References
[1] Casalino G 2018 Advances in Welding Metal Alloys, Dissimilar Metals and Additively Manufactured Parts (Basel: MDPI)
[2] Saha S, Usman Z, Li W D, Jones S and Shah N 2019 Core domain ontology for joining processes to consolidate welding standards. *Robotics and Computer Integrated Manufacturing* **59** pp 417–430

[3] Subrahmanian E, Rachuri S, Bouras A, Fenves S J, Foufou S and Sriram R D 2006 The Role of Standards in Product Lifecycle Management Support. *NIST Internal Report (NISTIR)* **7289** National Institute of Standards and Technology

[4] ISO -International Organization for Standardization- 2004 Industrial Automation System and Integration – Process Specification Language. Part 1, Overview and Basic Principles. ISO 18629–1 (New York: American National Standards Institute)

[5] Borgo S and Leitao P 2004 The Role of Foundational Ontologies in Manufacturing Domain Application *Proc. On the Move to Meaningful Internet Systems Conference* pp 670–688

[6] Solano L, Rosado P and Romero F 2014 Knowledge Representation for Product and Processes Development Planning in Collaborative Environments. *International Journal of Computer Integrated Manufacturing* **27** (8) pp 787–801

[7] Solano L, Romero F and Rosado P 2016 An ontology for integrated machining and inspection process planning focusing on resource capabilities *International Journal of Computer Integrated Manufacturing* **29** (1) pp 1–15

[8] Cali A, Calvanese D, Cuenca Grau B, De Giacomo G, Lembo D, Lenzerini M, Lutz C, Milano D, Möller R, Poggi A and Sattler U 2005 State of the Art Survey Deliverable D01. FP6-7603 – Thinking ONTolgiES (TONES)

[9] Chung P W H, Stader J, Jarvis P, Moore J and Macintosh A 2003 Knowledge-based process management an approach to handling adaptive workflow. *Knowledge-Based Systems* **16** (3) pp 149–160

[10] Guarino N 1995 Formal Ontology, Conceptual Analysis and Knowledge Representation *International Journal of Human-Computer Studies* **43** pp 625–640

[11] Lin Y 2008 Semantic annotation for process models: Facilitating process knowledge management via semantic interoperability. *PhD Thesis* Norwegian University of Science and Technology

[12] Lin H K, Harding J A and Shahbaz M 2004 Manufacturing system engineering ontology for semantic interoperability across extended project teams *International Journal of Production Research* **42** (24) pp 5099–5118

[13] Devedzic V 2001 Knowledge Modeling - State of the Art. *Integrated Computer-Aided Engineering* **8** (3) pp 257–281

[14] AENOR 2019 Especificación y cualificación de los procedimientos de soldeo para materiales metálicos. Especificación del procedimiento de soldeo. Parte 1. UNE-EN ISO 15609-1 (Madrid: Asociación Española de Normalización y Certificación)

[15] AENOR 2019 Especificación y cualificación de los procedimientos de soldeo para materiales metálicos. Reglas generales. UNE-EN ISO 15607 (Madrid: Asociación Española de Normalización y Certificación)

[16] AENOR 2011 Soldeo y técnicas conexas. Nomenclatura de procesos y números de referencia. UNE-EN ISO 4063 (Madrid: Asociación Española de Normalización y Certificación)

[17] AENOR 2006 Términos y definiciones para soldeo en relación con la Norma EN 1792. UNE-CEN/TR 14599 IN (Madrid: Asociación Española de Normalización y Certificación)

[18] ASME 2015 Boiler and Pressure Vessel Code Section. ASME BPVC.IX-2015 (New York: The American Society of Mechanical Engineers)