An Approach to Model Additive Manufacturing Process Rules

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***Abstract*—The building of small and complex metallic products by Additive Manufacturing (AM) has led to modified expert practices. While this technology opens up new horizons in terms of shape and geometry, it requires additional knowledge and various strategies to design and manufacture parts properly. In this context, for instance, trial and error or process simulations are used by experts to build the required knowledge base. This paper presents how simulation, experimentation, as well as knowledge construction, can complement each other and add value to solving the AM engineering problem and specifically manufacturing defects. The context and challenges of simulating a powder bed multi-layer process as well as characterizing AM knowledge are introduced in the first section of the paper. While the second section of the paper presents the state of the art related to simulation processes and AM knowledge management. The proposed approach highlights the need for integrating knowledge elements through both simulation and experimentation. This approach is then applied to a case study on the manufacture of lattice structures using EBM technology. The results highlight two benefits of this co-construction: a step-by-step method for research using simulation, and a knowledge model consisting of progressive stages leading to AM process rules. In conclusion, the study confirms that the proposed approach helps not only to map the AM activity but also to formalize its associated knowledge. The AM knowledge process thus acts as a support for the AM research process but is also nourished by simulation and experience, resulting in a continuous improvement cycle. Finally, this work brings perspectives from the development of AM knowledge modelling to CAM systems.**

***Index Terms*—Computer Aided Manufacturing, additive manufacturing, knowledge modeling**

I. Introduction and Context

EBM (Electron Beam Melting) is a layer additive manufacturing process that melts a metallic powder through electron beam technology [1]. This recent technology has changed expert practice, and the knowledge and know-how related to this process are still in development. EBM experts use various strategies to design or manufacture parts precisely but the knowledge of how the process occurs is not well understood or formalized. Among other solutions, elicitation is a means to capture crucial knowledge, [2] by having the experts express knowledge related to their activities. Elicitation is a necessary step to formalize their knowledge before structuring and sharing it with others. This research paper focuses on understanding the rules involved in the construction of AM process. Additionally, this paper is part of our ongoing research aimed at integrating AM knowledge into the Knowledge Management System (KMS) of an industrial environment. Our overarching objective is to capture knowledge related to AM practice, analyze it and organize it so it can be useful to CAM AM users. By studying each step of the knowledge management cycle, we intend to provide assistance to CAM AM users in their knowledge construction so it later becomes more stable and valuable to the whole AM community. To start with, this paper presents a progressive method for modeling AM process rules after an analysis of the work of AM experts. From the elicitation of working methods from AM experts, we attempted to understand the way knowledge is either mobilized or constructed during two major activities; EBM experimentation, and process simulation. From a knowledge engineering point of view, the intention is to show the progression of different knowledge categories until AM process rules emerge. Our first objective is to map the way EBM experts organize themselves when solving an AM engineering problem related to manufacturing. Secondly, our objective is to propose an approach for modeling AM process rules that emerge from the experts' elicitation so that they can be reused by CAM AM users connected to a KMS.

The research question we aimed to answer is: **which method should be proposed in order to have AM**

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knowledge emerge based on simulation and experimentation activities? To tackle this question the research methodology feeds on constructivism in a problem-solving situation. Two hypotheses were formulated as follows: knowledge can be located in an activity; and elicitation techniques applied in an activity (whether past or ongoing) helps to foster the creation and integration of knowledge.

In this paper, section two is dedicated to the state of the art (SoA) on multi-layer simulation for EBM which is, like trial-and-error experiments, a method for making knowledge progress. It is completed with a literature review on knowledge classification associated with the AM process. This led us to refine the initial research question in the following section and to describe the approach taken provide an answer. Section four presents a case study on lattice structures, followed by the test results. This specific test case is an example of how AM researchers handle complex manufacturing problems and strive to sort out recurrent technical and scientific issues thanks to various strategies. As a conclusion it is shown how experimentation and simulation can create AM process rules, thus enhancing the SoA and contributing to the evolution of AM knowledge.

II. Literature Review and Research Challenges

A. Multi-layer Process Simulation for EBM

Whatever the manufacturing technology is, simulation helps to better understand the process. For example, an offline process adjustment can be realized after having simulated it. For processes in which expertise is strong, such as machining, simulation serves only as validation. Whereas for other processes, like forging, simulation allows a choice of the manufacturing parameters. Fast and efficient simulation methods are used for many manufacturing processes. This is the case for example of forging for which simulation is done based on different process driving parameters and various characteristics related to the final part. Expert knowledge, in this case, allows for an enriched simulation, which in turn makes it more precise.

The same approach is applied to the EBM process and many research reports deal with simulating the EBM manufacturing process. For example, [3] thermal model simulates transient heat transfer to understand powder porosity and beam size impact onto the melt pool.

However, the focus is more on understanding the process than optimizing the manufacturing parameters. In addition, only a few millimeters of beam trajectory is simulated whereas a complete part simulation would require several kilometers of trajectory. Simulating the manufacturing process of a whole part is a work still in progress within the scientific community.

A recent study confirms that although the calculation time limits the simulation of an entire EBM build, “process simulation is a pre-requisite to strategy validation before the first build” [4]. Simulation is therefore used in this case to simulate precise zones or specific behaviors considered as potential issues, and enables a better understanding of the overall process. This method can be applied to the manufacturing of a whole part and helps to improve the knowledge of the community. Simulation is therefore a tool that can guide an expert in the knowledge maturing process. It becomes even more beneficial once coupled with experimental data as it combines AM theoretical knowledge with practice reference. However, as simulation methods are not yet able to simulate the whole EBM process, manufacturing parameters are set according to expert knowledge. It then becomes critical to capture AM knowledge through elicitation techniques. The following section gives an overview of the SoA related to elicitation and classification of AM knowledge.

B. Elicitation and Classification of AM Knowledge

Knowledge is created by individuals and, in this way, differs from data and information. Its tacit dimension makes it hard to formalize and communicate because it is personal and context-specific, whereas “explicit or “codified” knowledge is more transmittable in formal, systematic language” (Nonaka and Takeuchi citing [5]). As a critical part of the Knowledge Management (KM) process, elicitation helps to capture and formalize some aspects of the experts’ knowledge, so it can be codified later on in a KM system. During an elicitation about an AM process, experts explain to the Knowledge Engineer the various actions they undertake (i.e., what they do, how they act, why e.t.c.). Milton [6] proposes many individual knowledge elicitation techniques ranging from basic/explicit to deep/tacit knowledge, as well as from conceptual to procedural. Among them, process mapping helps to show how a task is performed, whereas concept mapping is used for modeling knowledge.

As far as the SoA on AM is concerned, most of research relates more to optimization methods than knowledge management. A recent study in the AM domain [8] characterized “AM crucial knowledge” as the knowledge that is critical to AM experts for designing and manufacturing a part properly. For instance, knowing which parameters have an influence (positive or negative) on the part quality is crucial AM knowledge. It also revealed four categories of knowledge (Examples, Influences, Rules, and Definitions), in relation to the activity of support creation for the EBM process. This was the outcome of a collective elicitation with six AM experts [8], using an influence matrix as an intermediary object to incite debate and argumentation. Two important elements are highlighted in the article. The first one is the identification of knowledge categories that could be used as a beginning for integration into KMS. A deep analysis of the rules leads to the distinction of State Rules and Action Rules, in connection with declarative and procedural knowledge respectively, commonly used by cognitive psychologists, and expressed through several conditions, such as: “if [statement] then [statement],” or “if [action] then [statement],” for a State Rule and “if [statement] then [action],” for an Action Rule.

The second element is the level of conviction an expert has in their vision of how the AM parameters influence the quality of the parts. In a collective elicitation process, expert knowledge emerges through the confrontation of heterogeneous levels of conviction. It gives rise to the construction of rules, which can be classified as the most prescriptive and explicit element in the model proposed by Ammar et al. [9].

C. Research Challenges

Based on the previous SoA, the focus of this paper concerns the most explicit part of knowledge that an EBM expert can express during the solving of an engineering problem. During problem-solving, intermediary solutions or unsatisfactory solutions are not preserved or formalized, and neither is the know-how. The research question is then how to target crucial AM knowledge in order to model AM process rules and memorize them for future use in new AM activities. In other words, the research is refined by the following question: **Within the framework of simulation and experimentation with EBM, how do tools, such as process and concept mapping, help to locate crucial AM knowledge which is useful for AM process rule formalization, construction, and maturing?** In the framework of a previous study on the activity of support creation for EBM [7], a methodology in three steps - Elicit, Analyze, Structure -was proposed for AM knowledge management. The same methodology was used by the knowledge engineer together with EBM researchers and was tested through a case study and validated as an approach. The idea is to show that solving an AM problem starts with an intuition of low conviction level, and ends up with the application of contextualized and explicit rules.

III. PROPOSED APPROACH

A. Objectives

The global methodology in this work is based on a constructivist approach. During an elicitation session EBM researchers are interviewed after they have built EBM parts. They are involved in a reflective analysis process with the help of the knowledge engineer. They explain and analyze the way an AM issue was solved. The outcome of this discussion leads to the development of a flowchart representing the rationale of the solving process. After each step of this process, an analysis is undertaken to identify the crucial AM knowledge categories, from a knowledge engineering point of view. A modeling process allows structuring and explaining of how AM knowledge evolves and matures until the AM process rules emerge.

Jonassen [10] showed that, in a problem-solving situation, people use various strategies to act and mobilize different types of knowledge (declarative knowledge and procedural knowledge, in relation to the activity or task they aim to achieve). Various strategies help AM experts gain knowledge improvement, for example, elicitation, experience feedback, observations, trial and error, simulation, e.t.c. The aim is to show that, in problem-solving analysis, the level of maturity of the AM experts' knowledge can improve through a knowledge engineering method that is based on AM activity mapping.

Below is the proposition of the approach for both the simulation of, and the practical EBM multi-layer process and the final structuration in terms of knowledge.

B. The Evolution of a Simulation Model and the Related Knowledge

When a part defect is observed after a production (or build) with EBM technology, the expert tries to find the reasons for this failure with the help of various strategies. Process mapping, used as an elicitation technique allowed the identification of the following steps in the solving method:

1. As soon as a problem was observed, the expert characterized the context.
2. The AM expert formulates a **hypothesis** about the possible reasons for the problem. This is done based on the current knowledge and experience of the expert.
3. The hypothesis is challenged and consolidated by a **literature review**. This helps to identify which **parameters** could influence the manufacturing conditions and therefore should be modified (for example, the EBM machine setup, the manufacturing parameters, the part specifications).
4. A **simulation model** is created and tested. It takes into account a series of physical laws. The simulation results confirm or not the hypothesis about the origin of the defect.
5. If this simulation confirms the hypothesis the **real-life manufacturing of the part** is launched, and the part quality is analyzed in order to check if the defects originally observed are obtained again. Going back and forth between simulation and experimentation is necessary to adapt and validate the parameters.
6. If defects correlate with the simulation model, the expert draws the **conclusion** that the selected machine parameters influenced the manufacturing.
7. Through a **new experimentation,** the same problem is applied to validate the hypotheses and the model.
8. If the results are conclusive, **a rule is validated** according to the context. Otherwise, the hypotheses are completed or adjusted by deepening the SoA and launching a new experimentation.
9. The procedure is confirmed or challenged as soon as a **new problem** or a **counter-example** appears.

In terms of knowledge engineering, the experts' reasoning and knowledge construction are analyzed. Below is the proposition of an approach to structure the knowledge related to AM and resulting from each step of the research process. It shows how the identified crucial AM knowledge improves while solving an EBM quality problem and highlights the occurrence, concepts, influences, justifications, and rules. As previously mentioned [7], influences and rules were captured as categories in a former AM elicitation. In this specific research, occurrence, concepts, and justifications are new interlinked knowledge items that enrich the knowledge base. The observation of a defect constitutes an occurrence, i.e., an isolated case characterizing a part defect. For instance, a diameter problem, a surface quality defect in relation to the EBM manufacturing conditions. If this defect reappears after several EBM builds, this becomes a set of recurring cases. The occurrence is then characterized by the precision of the problem as well as the contextualization of the problem. This is the starting point for feeding the knowledge base. A systemic analysis of the influencing parameters was done by exploiting the current expert's knowledge. For instance, the part specifications, the machine setup parameters, as well as the manufacturing parameters. This gives possible explanations about the link between the parameters and the defect. The creation of a basic concept map helps to track the relationships between the main high-level parameters. In order to solve the hypothesis, any possible influence between the concepts is formalized by applying; "if this parameter is modified in this way it may have an influence on this element". This intuition is confirmed after several trial-and-error approaches using simulation and experimentation. The research protocol is documented and contains the theoretical and experimental explanations that constitute a justification base. The knowledge base is enriched by these solutions.

As soon as the results of the simulation and experimentation match, influence statements are validated. A low-level influence map highlights four relation types between the concepts (linked by "is defined by," "is part of," "impacts" or "depends on"). The final procedure of how to solve this AM problem can then be confirmed. It is composed of process rules (or mathematical law). The process and knowledge co-evolution process is summarized in Fig. 1.

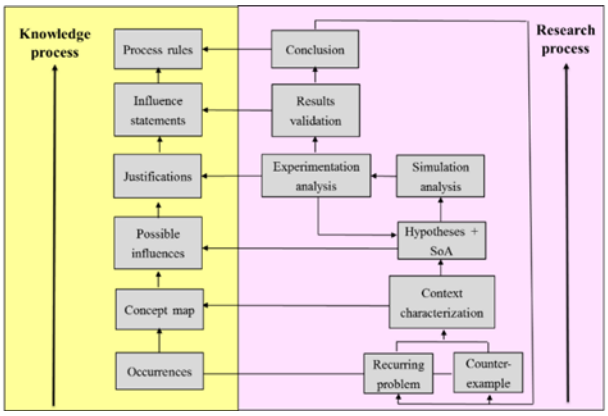

Figure 1. Knowledge and research co-evolution process.

The following case study gives an example of the evolution process of knowledge by a mix of simulation and experimentation of vertical struts built with EBM.

IV. Case Study about Lattice Structures

This case study is an example of knowledge engineering for AM when analyzing the activity of building struts with EBM. A lattice structure is one possibility that EBM technology can offer and is composed of a network of small struts. Its dimensional and geometric quality is influenced by many process parameters. Simulating the process helps the experts to choose the best process parameters and, together with the experimentation, obtain the correct dimensional accuracy.

The task of building small struts properly is presented below to show the knowledge process during this research experience, as well as the method that can be followed to capture AM crucial knowledge, especially the solving rule. Generally speaking, the elicitation exercise took the form of a reflective interview, similar to a brainstorming session, with precise questions about "the **What,**" "the **When,**" "the **How**" and "the **Why.**" For instance, "What was wrong according to you?" and "When did it occur?" helped define the problem. "How would this parameter influence it? What did you do to solve it?" led to possible influences or solutions. "Why did you think this parameter has an influence? Why is this not part of the SoA?" gave justifications to the proposed explanations.

C. Experimentation Summary

The section below summarizes the narrative description of the EBM experts when they were interviewed about their AM activity. In the EBM research led by Béraud et al. [3], the requirement was to build fully dense small cylindrical struts with a nominal diameter of 1 mm, provided by a CAD model. However, after tomographic measurement, a quality defect was observed since the final strut diameter was 343 μm less than the nominal value. In a report on building lattice structures [11], Suard confirmed that the whole set of vertical struts possesses a diameter below a nominal diameter. Experts understand that this problem is obviously linked to some EBM machine parameters and that simulation is necessary. To overcome this geometrical defect, the parameters that influence the build need to be adjusted. A literature review gives partial explanations because the models proposed in the SoA do not take into account all the parameters. EBM technology is recent and researchers have to create their own knowledge by the association of simulation and experimental work, and by trial and error.

D. Process Analysis Based on the Proposed Approach

After this unstructured interview, the experts were asked by the Knowledge Engineer to analyze step-by-step their research activity in order to map the process. EBM researchers used the following reasoning.

Step 1 (Problem): After recurring builds of the vertical struts, experts notice a problem about the **struts' geometry**. Tomography shows that the struts' diameters are smaller than the nominal diameter.

Step 2 (Context characterization): To better characterize the problem and find the diameter of a built strut, experts make a logical link between the strut diameter problem and the melting, specifically, the **melting zone** (i.e., the overall zone melted by layer) which seems too small to melt the nominal diameter. The melted zone depends on the **melting strategy** of the EBM machine. They know also that the melting strategy is composed of the beam trajectory and the beam parameters. The trajectory can be, for instance, hatching and contour. The beam parameters are characterized by the speed, the diameter, and the power, (i.e., voltage U and current I) of the beam. In parallel, the machine parameters are retrieved. They concern the contour offset, beam focus current, beam intensity and beam speed.

Step 3 (Hypotheses): Based on their experience and current knowledge, experts speculate as to the reasons why the diameters are smaller than the nominal diameter. Since "the strut has not been melt till the boundary," the melting pool (i.e., the melted zone around the beam at any instant) may not be tangential to the nominal diameter. A literature review confirms that the melt pool width and offset do not match (offset is half the diameter). However, the melt pool diameter cannot be modified or controlled as it is not a direct machine parameter; it depends on the focus current, the beam speed and beam current. It is then necessary to simulate the melting process in order to optimize the diameter and to know the temperature distribution at each layer, especially the whole set of points where the temperature is above 1665 ℃. Indeed, these points belong to the melted zone and form the strut geometry. SoA also provides models for melting with beam diameter (Φ), beam current (I), beam speed (V), and beam trajectory as inputs. Yet, the beam diameter (Φ) is unknown, what is known is I_f, the focus current (also called the focus intensity). This diameter would then vary according to the machine **focus current** (Φ = f (I_f)). To check the influencing factor of the focus current and to check the hypothesis about the beam diameter, a thermal simulation of the strut building seems to be a solution for understanding the temperature distribution and beam diameter, and consequently the diameter of the built strut. The current literature on thermal simulation indicates that the use of a Finite Elements (FE) method is adapted to EBM technology.

Step 4 (Simulation and experimentation trials): A FE model is then created. This model takes into account a series of physical laws [3]. Once the model is finalized, the build of a vertical strut is simulated. In parallel, experimentation to calculate the beam diameter as a function of the focus current is launched. Both theoretical and real results are analyzed after simulation and experimentation. They show that the trajectories do not suit, and especially that the value of the **contour offset** is wrong. At that step, a loop is done using a former hypothesis and a new hypothesis is then highlighted: the contour offset may not be well handled, and especially the first outer contour offset would be determined during strut building. The launch of a real-life building experimentation f (I_f, I, V) with an incorrect contour offset value leads to the same conclusion: the strut quality examined at the output of the machine shows defects.

Step 5 (Results validation): Experts conclude that melting can be simulated from the machine parameters by considering a) the Finite Elements which take Φ, I, V, and the trajectory as inputs; b) the link between If and Φ. The melting pool diameter, and, therefore, the contour offset, can be determined. Strut defects can therefore be correlated to the simulation model.

A new build of struts is launched with the new parameters and there is no default.

Step 6 (Conclusion): The final conclusion is that melting can be simulated from the machine parameters in order to determine the melting pool diameter and then the offset. **The first contour offset influences the manufacturing of the struts and therefore their diameter.**

A process rule can now be developed to determine the value of the first contour offset based on the beam parameters. The test of this mathematical model is repeated with many struts of different diameters and is then validated. However, struts above 5 mm diameter exhibit porosity; this means the rule only has validity under certain conditions. Further research then needs to be conducted to extend the process rules.

E. Results in Terms of AM Knowledge Structuration

As far as the knowledge process is concerned, the following steps were identified from this case study. They correspond with the stages of the research process.

Step 1: The occurrence relating to the **struts diameter defects** is a starting point for characterizing the problem. Its description is completed by the definition of the context with the part's nominal geometry, the EBM build themes that manage melting, log files e.t.c.

Step 2: The main concepts involved in this problem are the **strut geometry, the melting zone, and the melting strategy**. (See Fig. 2).

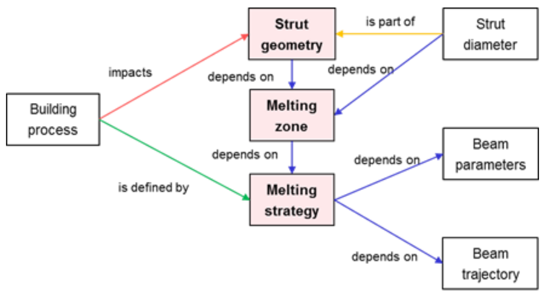

Figure 2. High-level concept map for the building of vertical struts.

Step 3: The relationship mapping between these three concepts leads to a list of possible influencing parameters, namely: the **beam trajectory** and the **beam parameters**. The latter are more precisely the speed, the focus current offset, and the power.

Step 4: The new simulation model and the associated experimentation setup confirm the link between the trajectory, Φ, I, and V with the strut diameter. Both research experiences are documented and formalized by the experts. As **supporting examples,** they feed the knowledge base with their justifications for problem-solving.

Step 5: The high-level concept map is completed by a detailed relationship map, and shows the influences between the EBM parameters. It proves that the beam diameter varies according to the focus current in the machine ($\Phi = f(If)$) and is also impacted by the contour offset. (See Fig. 3).

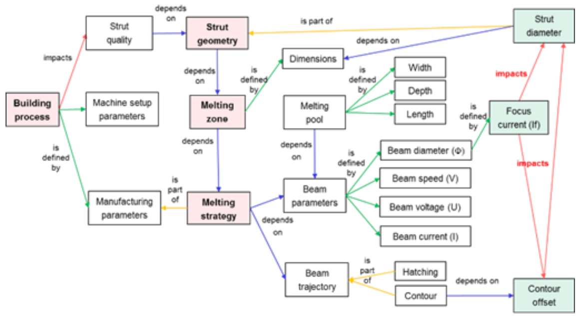

Figure 3. Detailed relationship mapping for vertical strut building

This low level graph shows the decomposition of the concepts, which leads to the identification of the two main interconnected parameters: contour offset and focus current. Experts can thus state that, to build a strut with a correct diameter, their mathematical simulation model enables to fix these two parameters. The red arrows, labeled "impacts," on the right side of the map are characterized by this law.

Step 6: The last step of this knowledge engineering process is the confirmation of the final rule summarized by this law or formula:

(strutDiameter) = F (I_f, I, V, contour Offset) where I_f is the focus current, I the current, and V the beam speed.

V. Conclusion

This research paper is based on the manufacturing of metallic parts using EBM multi-layer technology, which is a recent process for industries. Its objective was to propose an AM knowledge engineering method for capturing knowledge categories and modeling them in a KMS. It is recognized that AM knowledge is not yet stable and likewise is of different maturity levels as it encompasses various scientific domains [11]. It evolves dynamically through the confrontation of generic scientific theories, local skills, and individual knowledge that emerge in the practice. The resulting research question is how to enable the identification and the capture of new AM knowledge items. The approach proposed here is a three-step method (Elicit-Analyze-Structure), used during a reflective EBM problem-solving process. Process mapping is used as an elicitation technique to understand the reasoning of experts when tackling an AM problem **reference**. Concept mapping helps to visualize the main concepts involved in the knowledge creation. In a case study on lattice structures, the EBM process was studied from a scientific and engineering point of view. It is formalized by the development of a process map. This outcome acts as an intermediary object for analyzing the knowledge construction behind the experts' activity. The results show a maturing process, from a problem to a solution, as well as the knowledge elements that match with the step-by-step AM process. Occurrence, concepts, influences, justifications, and rules are thus captured. This work shows that the combination of simulation and experimentation acts as leverage to expert knowledge evolution. It is reinforced by the experts' reflective practice, which structures the AM crucial knowledge. This proposition is also a means to assist AM experts in the development and capitalization of long-lasting action rules. In an AM activity, characterizing occurrences, mapping concepts to identify the main influencing parameters, storing the data and process rules resulting from simulation and experimentation would indeed guide the experts in their decisions. These elements complete the former proposition based on a collective elicitation and influence matrix for capturing AM knowledge. The next step will be to classify the knowledge items into a KMS and integrate the experts' level of conviction. Lastly, this modeling method requires its application to other case studies with EBM users and other AM technologies. Some first steps will be to proceed with our case study and to test how this law and associated process rules operate under different conditions; for example, struts with bigger diameters, test parts with another geometry. That is, any critical research cases dealing with trial-and-error methods with experimentation and simulation, and where process rules are still unclear or intermediate solutions have not been formalized.

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