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Position Paper

The "AluTrace" Use Case: Harnessing Lightweight Design Potentials via the Materials Data Space®

Martin Huschka[1], Michael Dlugosch[1], Valérie Friedmann[2], Elena Garcia Trelles[2], Klaus Hoschke[1], Ulrich E. Klotz[3], Sankalp Patil[1], Johannes Preußner[2], Christoph Schweizer[2], Dario Tiberto[3]

[1]Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, EMI, Freiburg, Germany;
[2]Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, Germany;
[3]fem Research Institute for Precious Metals and Metal Chemistry, Schwäbisch Gmünd, Germany

Abstract

Due to the great freedom of design, additive manufacturing (AM) offers enormous potential for lightweight design. In order to harness this potential, it is crucial to integrate knowledge between the individual stages of the AM value chain. By digitally linking AM process and product data, lightweight design and production can be further optimized in economical and ecological terms.

The use case discussed here describes a design engineer who optimizes an aluminum component originally manufactured by casting with regard to lightweight design by means of topology optimization for AM. A process-specific topology optimization algorithm (PSTO) provides an optimized design and also knowledge about the best suited combination of AM-machine and corresponding process parameters. As input for this design algorithm, data about mechanical material characteristics, AM process parameters and post-processing information is required. Such heterogeneous data needs to be automatically integrated after being retrieved from a cross-institutional data space.

Since the heterogeneous data is provided by different actors, compliance with the FAIR principles [1] is paramount. To meet this need, a data space architecture based on the International Data Spaces (IDS) reference architecture model [2] is designed and implemented. By doing so, the authors create the very first instance of the Materials Data Space® (MDS) [3]. Using the MDS in this context ensures findability (F) of the decentralized data, secure access (A) to the data via standardized protocols and a trustful ecosystem, data and systems interoperability (I) for multilateral data sharing and reusability (R) of the data due to rich metadata in form of knowledge graphs. The knowledge graphs describe the entire AM process chain semantically and embed the resulting data in its context through an ontology-based process model. This semantic metadata enables data linking in the sense of a cross-institutional data fabric with the aim of automated analysis for an intelligent lightweight design via PSTO.

When using the decentralized data from the MDS, the design engineer is empowered to provide an optimized lightweight design that results in a weight reduction of 23 percent in comparison to the cast component. Furthermore, the lightweight design demonstrates significantly improved properties compared to a geometry designed according to the previous state-of-the-art in topology optimization without linkage of material and process data via the MDS.

The AluTrace use case demonstrates the benefits of a cross-institutional data space in a real-world scenario that further exploits the AM lightweight potential.

Contact:
Martin Huschka
Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, EMI
Ernst-Zermelo-Strasse 4, 79104 Freiburg, Germany
martin.huschka@emi.fraunhofer.de
www.emi.fraunhofer.de

1 Use Case Description

The aim of the "AluTrace" research project was to digitally link the data and knowledge silos that arise over industrial product development and manufacturing cycles. The project consortium, consisting of the Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, EMI, Fraunhofer Institute for Mechanics of Materials IWM and fem Research Institute for Precious Metals and Metal Chemistry, designed a realistic use case for this purpose in consultation with experts from research and industry.

The use case aims to optimize a component, originally manufactured by casting an aluminum alloy, with regard to lightweight design. By means of topology optimization for additive manufacturing (AM), a weight reduction of 20 percent should be achieved while maintaining the same mechanical performance as the cast component, see Figure 1.

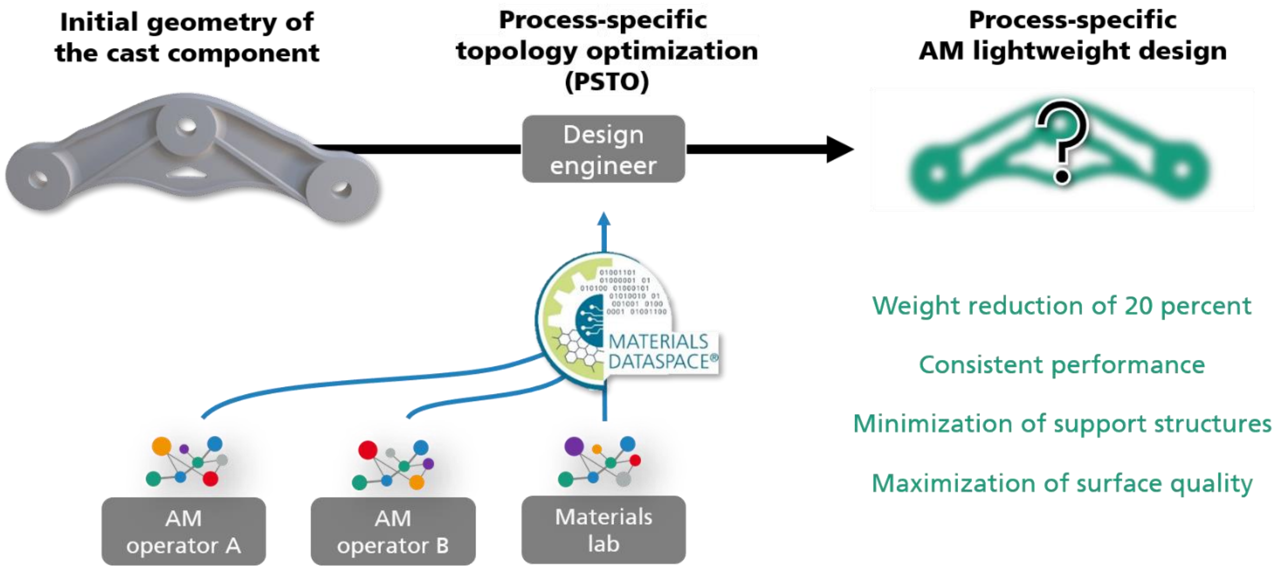

Figure 1. The goal of the AluTrace use case is to enable a design engineer to optimize the initial geometry of a cast component for lightweight design with AM using PSTO interacting with data providers via a data space. Image: Fraunhofer EMI

For this purpose, a new algorithm for process-specific topology optimization (PSTO) is to be implemented. It should link data across institutions and exploit heterogeneous material and process data for the design. A data space is required that enables the PSTO to (a) select the most suitable laser powder bed fusion (LPBF) manufacturing system of all actors in the data space and to (b) adapt the lightweight design and AM process parameters according to the data provided by the actors. The data space should offer a virtual marketplace to find suited data providers and allow for trustworthy and secure data exchange amongst them under highest data sovereignty standards.

The following actors located in different institutions take part in the AluTrace use case:

- A design engineer performs the lightweight design optimization of the component for LPBF. The design engineer is open to the choice of a specific AM machine located at the AM operators and makes the decision dependent on the best part quality to be achieved.
- AM operator A owns LPBF manufacturing system A and provides AM process data for components additively manufactured on this system.
- AM operator B owns LPBF manufacturing system B and provides AM process data for components additively manufactured on this system.
- The materials laboratory (lab) performs component post-treatments, tests AM components, investigates materials experimentally and provides the collected material data.

2 Data Space Architecture for Cross-Institutional Data Sharing

The interdisciplinary field of materials science and engineering (MSE) studies the microstructure and the characteristics of materials as a result of the manufacturing process in order to design materials and structures with the best quality for a certain real-world application [4]. Due to the diversity of material structures from atomistic to macroscale and the various models to describe them, MSE data can be characterized by its heterogeneity, complexity and fragmentation [5–7]. With the aim of comprehensive data collections, several attempts for digitization of MSE data have been made. Accordingly, a multitude of materials databases have been set up in order to provide information, e.g., about material properties, test specifications, process knowledge or sources of supply [8–15]. Although these data sources count as reliable, they often lack provenance and timeliness. With the aim of interoperable data with extensive linage, others use comprehensive metadata structures [16, 17], strive for an up-to-date and data-rich collection through automation of (meta)data structuring [18, 19] or provide platforms for digital workflows in the MSE domain [20–24]. To counteract siloed solutions, several initiatives were launched to harmonize the MSE digitization efforts of the community [7, 25–30]. And as the demand for data sharing increases, so does the need for a commercial marketplace for MSE data, which is why centralized solutions are already under development [31, 32]. Although reference architectures for decentralized data marketplaces already exist [2, 33–37], material-related use cases focus either on production [38–40], supply chain management [41, 42] or product life cycle management [43].

With the aim of providing cross-institutional data along the entire MSE value chain, the Materials Data Space® (MDS) initiative was founded in 2015 [3]. Although it is not the only initiative for a data space in materials science [44, 45], no implementation for a decentralized infrastructure for MSE data sharing under highest data sovereignty standards is known to the authors. In the present work, the authors designed and implemented a data space architecture based on the International Data Spaces (IDS) reference architecture model (RAM) [2], see Figure 2, and present the very first implementation of the MDS.

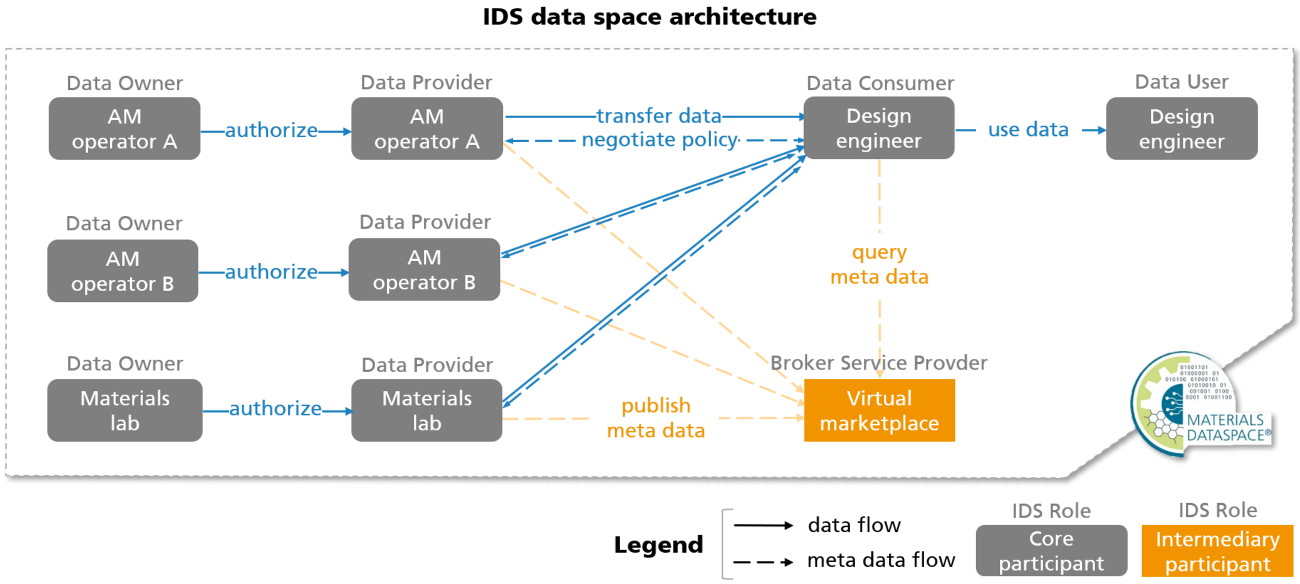

Figure 2. Cross-institutional data space architecture, based on the IDS-RAM [2]. The business layer shows the actors, their standardized IDS roles and IDS interactions. The technical implementation represents the Materials Data Space® [3]. Image: Fraunhofer EMI

IDS connectors, here the Dataspace Connector [46] (DSC), were configured and set up for each actor in the data space. IDS certificates were acquired and digitally signed JSON web tokens were obtained from the IDS identity provider in order to be able to participate in the IDS. Triple stores were connected to the DSC as data sources. These provide SPARQL endpoints that can be queried over the DSC as soon as the usage policy negotiation between the DSCs of two actors was successful. The finalized contract agreements and data usage is logged to the IDS clearing house. The IDS connectors are registered at an IDS metadata broker that serves as a virtual marketplace. It helps MSE data consumers to find potential MSE data providers in the data space. Furthermore, an application interface between the PSTO as data sink and the data space was established, see Figure 3. This enables the PSTO to automatically query material characteristics and matching AM process parameters in the data space.

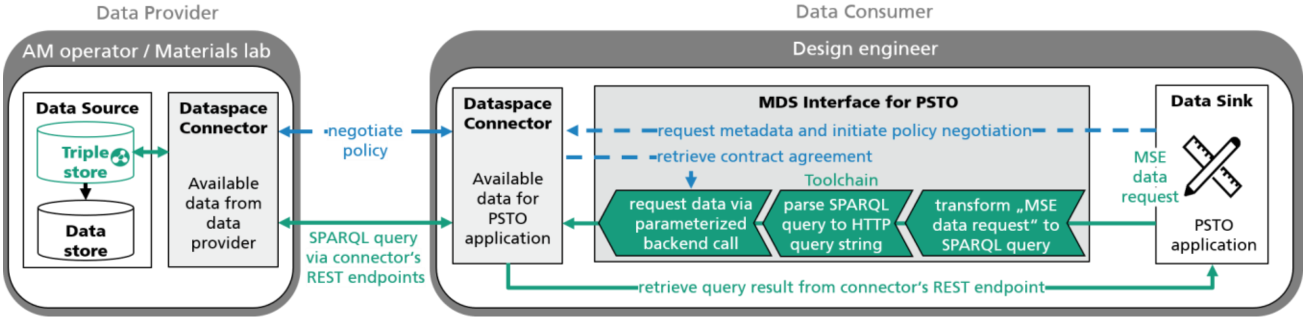

Figure 3. Application interface between the PSTO and a data provider in the data space. Image: Fraunhofer EMI

3 Semantic Data Structuring and Linking

If heterogeneous data is to be shared by several actors, compliance with the FAIR data principles (findable, accessible, interoperable, reusable) [1] is paramount. The implementation of this use case by means of the MDS ensures

- to find the decentralized data and their providers through the use of a graph-based virtual marketplace, i.e. an IDS broker, that is searchable by semantic metadata,
- secure access to the data via the https protocol and trustful communication through the IDS identity provider as authentication and authorization service,
- interoperable data through semantic web standards and systems interoperability through IDS standards,
- reusability of the data due to machine- and human-understandable metadata in the form of knowledge graphs (KG).

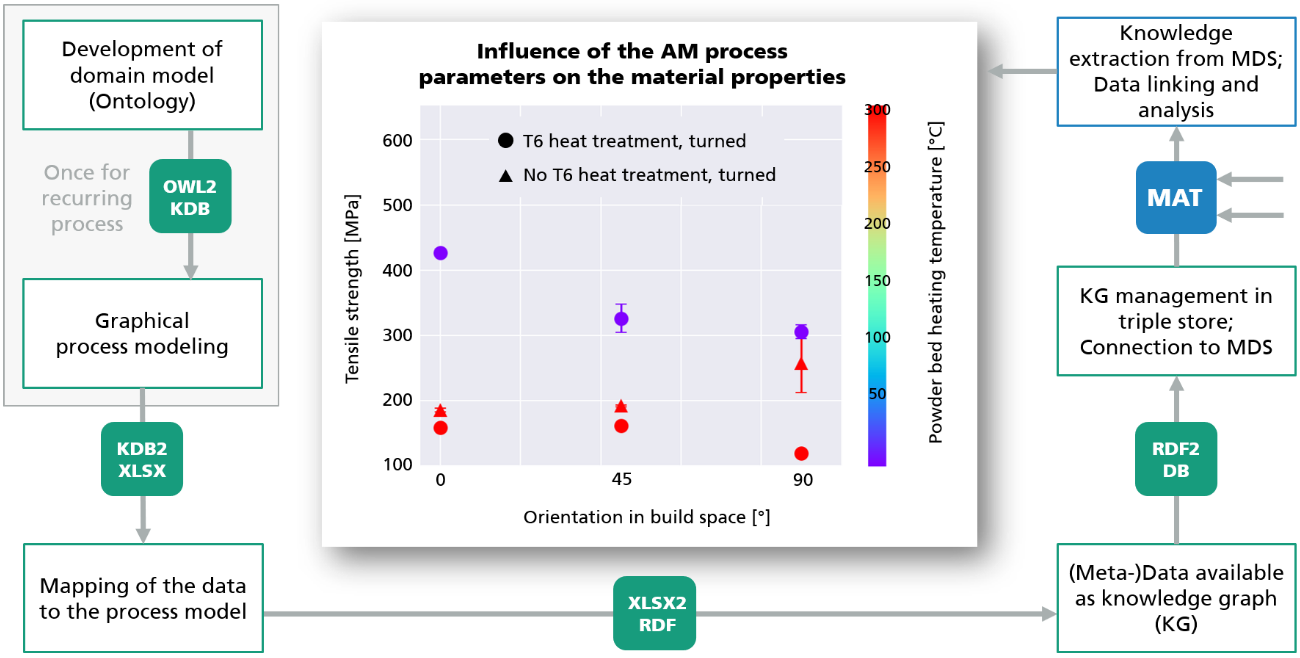

Figure 4. Workflow for generating semantic process metadata by the data provider (green) using the Fraunhofer IWM toolchain. The query of data from multiple data providers is performed by the data consumer (blue). In the center, an exemplary plot is shown that is result to cross-institutional data linking and analysis. Image: Fraunhofer IWM, Fraunhofer EMI

The RDF-based KG describe the entire value chain from AM to mechanical testing and map the data to its context in the process through an ontology-based process model, see Figure 4. This traceable and interoperable process metadata is managed by the data providers in their own triple stores that are connected to the MDS via their DSC. With these MSE domain specific KG a cross-institutional data fabric is established through linked data principles. Hence, the design engineer as data consumer is able to exploit the heterogeneous MSE data provided by the different actors.

4 Added Value in the Use Case

A new algorithm for topology optimization has been developed that is connected to the Materials Data Space® in order to enable efficient utilization of material and process data linked across institutions. Through this, real measured material properties related to the specific manufacturing equipment and process parameters can be used for the design. Compared to the use of non-specific sources, e.g., from databases, this greatly reduces the uncertainty of material properties and thus creates additional lightweight design potential.

In the present use case, the PSTO with connection to the MDS enables the design engineer to find an optimized and process-specific lightweight design. By means of the PSTO, an optimized lightweight part was designed with a weight reduction of 23 percent compared to the cast component. In addition, the lightweight design exhibits improved properties compared to a component geometry designed according to the previous state-of-the-art of topology optimization without exploiting the MDS: increased safety under overload by +15 percent and greatly improved AM process variables such as -67 percent support structures as well as +16 percent surface quality.

The AluTrace use case demonstrates the benefits of a cross-institutional data space in a real-world scenario that further exploits the AM lightweight potential. Within the scope of the project, further material and process data was collected. With the Materials Data Space® as a scalable data space, it will be possible for data providers and consumers to maximize the material and structural design potentials in many MSE applications in the future.

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