Digitalization of Material Properties Across the Entire Process Chain

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Steel and metal-intensive industries are advancing digitalization beyond traditional ERP, PLM, and MES systems to more effectively integrate materials technology and manufacturing processes within enterprise IT environments. This paper presents a materials management system based on a scalable JSON data structure that consolidates test data, process histories, CAE model libraries, and decision workflows. A central feature is a semantic knowledge graph that links material properties with process data across the entire production chain. This integrated approach enables faster product development, improved process control, and supports downstream applications such as Wire and Arc Additive Manufacturing (WAAM).

KEYWORDS: DIGITALIZATION, MATERIALS DATABASES, STEEL INDUSTRY, MATERIAL PROPERTIES, PROCESS HISTORY, KNOWLEDGE GRAPH, CAE, WAAM

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INTRODUCTION

Digitalization in the steel industry requires a comprehensive framework that integrates material behavior, production processes, and end-to-end traceability. This next phase of digital evolution focuses on capturing dynamic material states across the full manufacturing chain, including advanced downstream processes such as Wire and Arc Additive Manufacturing (WAAM). Strategic knowledge management is critical for preserving operational expertise and accelerating the onboarding of new personnel. Reliable decision-making depends on access to structured knowledge from past projects, including test data and process records. Linking this information with material master data via integrated reference databases enables effective knowledge reuse. By combining materials engineering with digital infrastructure, this approach enables precise control of material properties throughout the entire process chain. It optimizes factors such as alloy design and energy use, improving efficiency and supporting the rapid development of innovations like green steel production.

Matplus EDA® provides a practical infrastructure with a scalable database, microservices, mathematical functions, and flexible visualization tools in multi-user environments (1). It is used across various industrial companies as a central platform for materials engineering, from modeling and data analysis to decision support. This paper shows the digitalization of material properties across the entire process chain, including downstream processes like Wire and Arc Additive Manufacturing

(WAAM) and ooperations such as heat treatment and machining, based on findings from the publicly funded DAF (Digital Aerospace Factory) project.

1. Digital Material Infrastructure

The EDA® infrastructure consist of a JSON backed database, a Python based middleware and a web frontend based on FOSS (free and open source software) technologies. It integrates and harmonizes various data sources and tools, including:

- **Reference Databases:** The system consolidates key material databases, including Stahldat SX® for steels and polymers, and can be extended with sources like MMPDS for aerospace (2,3). These serve as a foundation for company-specific material data management, linking upstream inputs with downstream decision-making to enhance traceability and technical reliability.
- **Materials Selection and Assignment:** Material data and material cards provide a consolidated single source of truth for materials information. A streamlined app supports downstream applications such as CAE, and enables efficient material selection and assignment during product development through a lean and intuitive interface.
- **Lab and In-line Test Data:** Incorporates standardized formats such as SEP 1240, VDA 239-301, DIN SPEC 9012 ensuring that test data is systematically captured and utilized.
- **Knowledge Graphs:** Display the evolution of materials properties along complete manufacturing routes with several process steps in a comprehensive way.
- **CAE Model Libraries:** Supports a range of material models like Johnson-Cook and Ramberg-Osgood, facilitating comprehensive simulations and analyses-
- **Seamless CAE Integration with Python Tools:** Utilizes Python-based tools such as SciPy and PyLife for advanced data analysis and fatigue evaluation, enhancing the system's analytical capabilities

This digital infrastructure supports advanced material and process optimization across all stages of product development and manufacturing. A key capability is the end-to-end tracking and management of material property evolution throughout the process chain. This includes linking process parameters with material models to predict behavior and performance. The approach was demonstrated in the Digitale Aerospace Fabrik research project, where it was applied to a steel component manufactured via WAAM, followed by heat treatment and machining. The effectiveness in a practical application could be demonstrated regarding microstructural analysis, and integrated modelling for technology development.

2. Process Flow Analysis

To systematically represent end-to-end manufacturing and the evolution of material properties within the materials management system, a knowledge graph based on a Directed Flow Graph architecture was adopted. This framework models each manufacturing process as a node, with directed edges capturing relevant process data like temperature-time-series as well as the evolution of material properties between these processes. The approach emphasizes process-centric representation, flow conservation, and graph extensibility (4).

A visual process modeling environment supports structured modeling and interactive configuration of complex flows within manufacturing processes. The system features a modular interface with five core GUI components: Tree Browser, Workspace, Tool bar, Nav Bar and Popup forms. This architecture enables high interactivity and maintains modeling efficiency for engineering users. The modeler allows intuitive model construction via a drag-and-drop interface without requiring programming expertise.

The system uses JSON objects as the core data structure, enabling standardized serialization, storage, and transmission. Each graph model can be exported as a JSON file compatible with back-end databases such as MongoDB or used as input for downstream computation modules. The data scheme supports nested structures and extensible attributes, enabling high-dimensional process representation. The editor features strong extensibility and responsive design, supporting multi-material flows, branching process paths, and multi-layer modeling, making it suitable for complex scenarios like additive manufacturing and distributed production.

Fig. 1 shows the downstream process chain for manufacturing a part via WAAM, heat treatment, and machining.

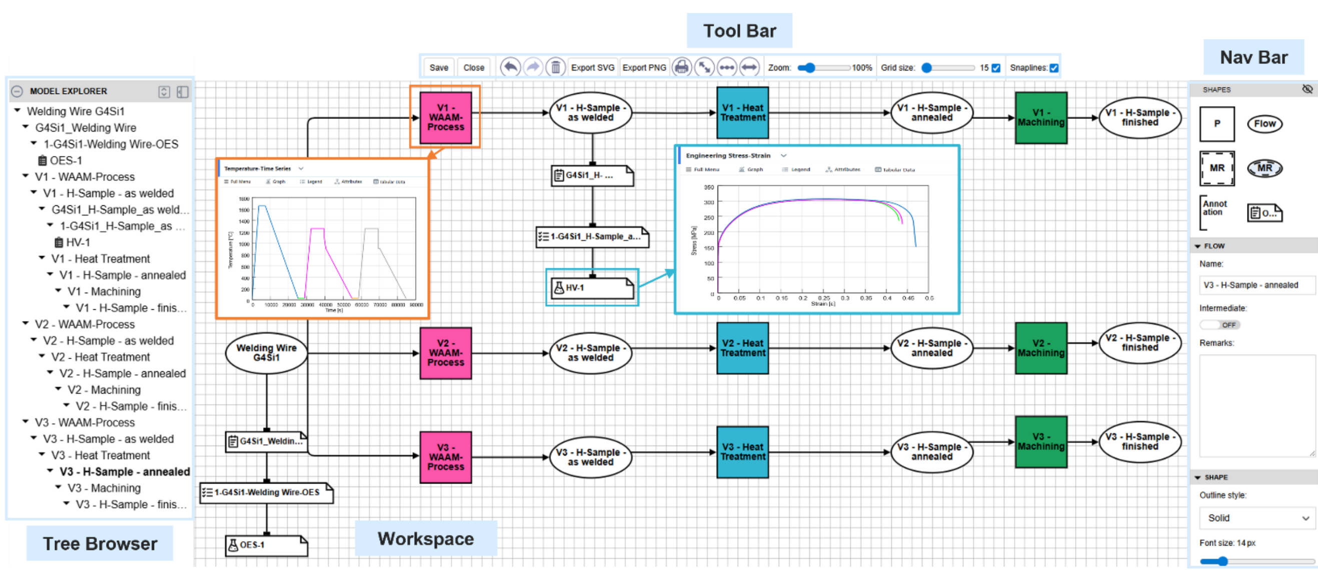

Fig. 1- Graphical Process-Flow-Analysis modeler integrated in EDA® showcasing evolution of materials properties of a WAAM manufacturing route with process data (orange) and test data (blue)

Processes are displayed as colored squares, ellipses represent material conditions and rectangles were used for test date in the format of a work-break-down-structure (order, batch, test). This semantic linking combines process data (example orange box) and material testing (example blue box) for accurate analysis and precise predictions and also simplifies modeling with the intuitive modeler including a seamless data import via flexible importers.

3. Exploratory Data Analysis

Exploratory Data Analysis (EDA®) plays a central role in transforming raw process and material data into actionable insights. To support this, the digital infrastructure enables the creation of aggregation tables that consolidate selected data points from process flows and the underlying knowledge graph. These tables serve as a structured basis for targeted analyses across the entire process chain. Graphical exploration tools allow users to visualize trends, correlations, and anomalies in material behavior, while integrated curve-fitting functions support the identification and parametrization of relevant material models.

A practical example originating from the DAF project includes data from materials simulation using JMatPro®, where thermo-physical and phase transformation properties are aggregated to assess their impact on downstream processes (Fig. 2). Visual analysis and curve fitting help identify trends across alloy compositions and support model calibration for CAE and process optimization.

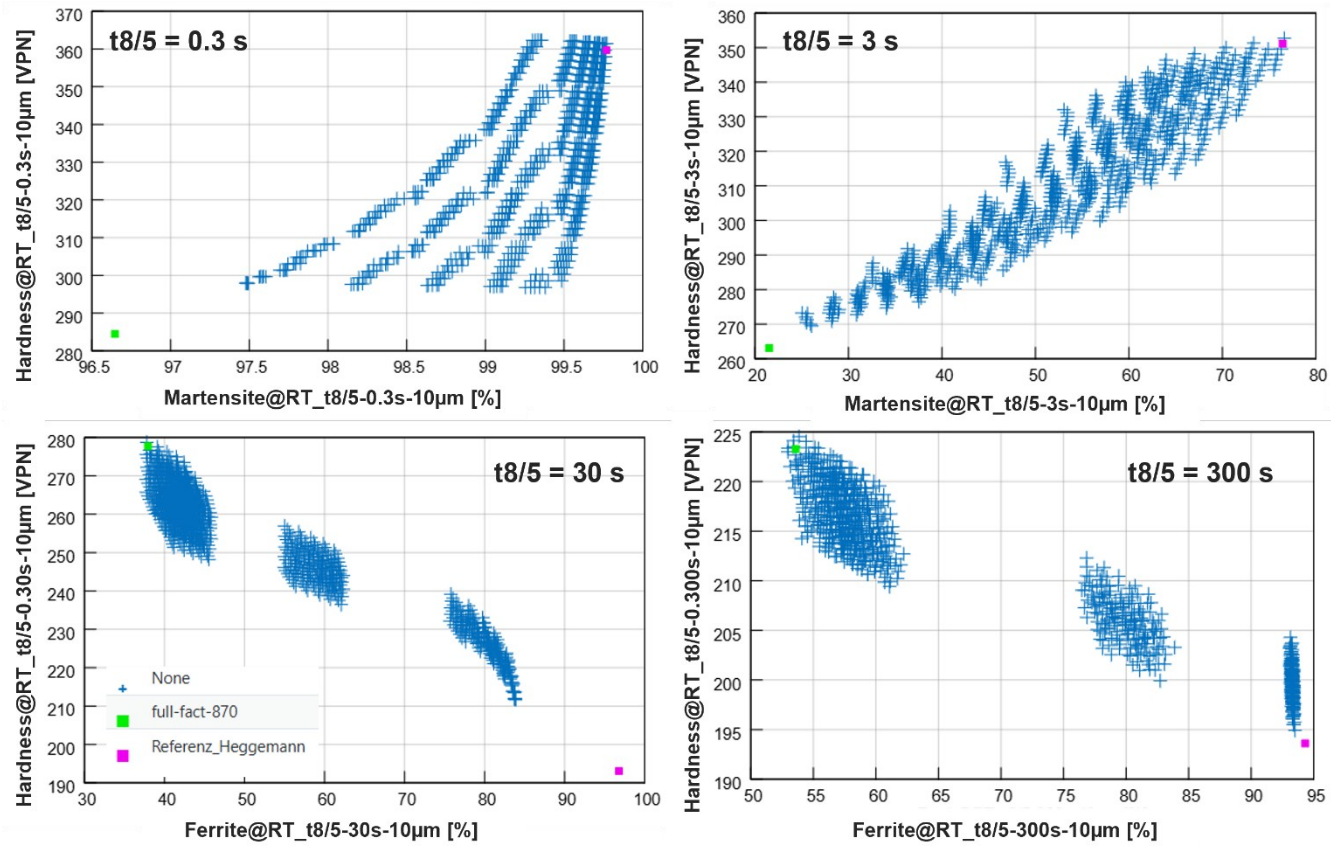

Fig. 2 - Overview of hardness results from JMatPro® calculations over microstructure proportions depending on t8/5 times: upper row martensite, lower row ferrite

The figure shows the simulated impact of different cooling rates on the microstructure and resulting hardness of the welding wire material G4Si1 for a full-factorial design of experiment.

4. Material Card Generation

The materials management system supports the entire workflow from test data evaluation to system-neutral CAE material cards (1,5,6). It is built on three pillars:

- **Harmonized Data Structure:** JSON-data format is used to link material models to master data and lab results, ensuring compatibility across systems.

- **Infrastructure for Scientific Tasks:** Stores and parametrizes constitutive equations, supports curve fitting, and integrates Python tools for advanced analysis. It also incorporates external FOSS libraries for extended functionalities.

- **Import/Export Functions:** Facilitates flexible import/export of material cards between systems, consolidates cards from various platforms, and provides internal visualizations for comparisons.

This approach improves traceability, efficiency, and data security across diverse CAE environments.

5. Workflow Automation

To simplify operations and improve traceabilty, the materials management system includes an integrated workflow editor and engine based on BPMN 2.0 (Business Process Model and Notation) and DMN (Decision Model and Notation). These workflows coordinate tasks across departments with notification features and automated plugins, ensuring end-to-end traceability and standardization. By aligning with BPMN and DMN, they reduce implementation and operational costs through lean, efficient execution. In the DAF project, several such workflows were deployed, including one for automated weld seam inspection, as shown in Fig. 2.

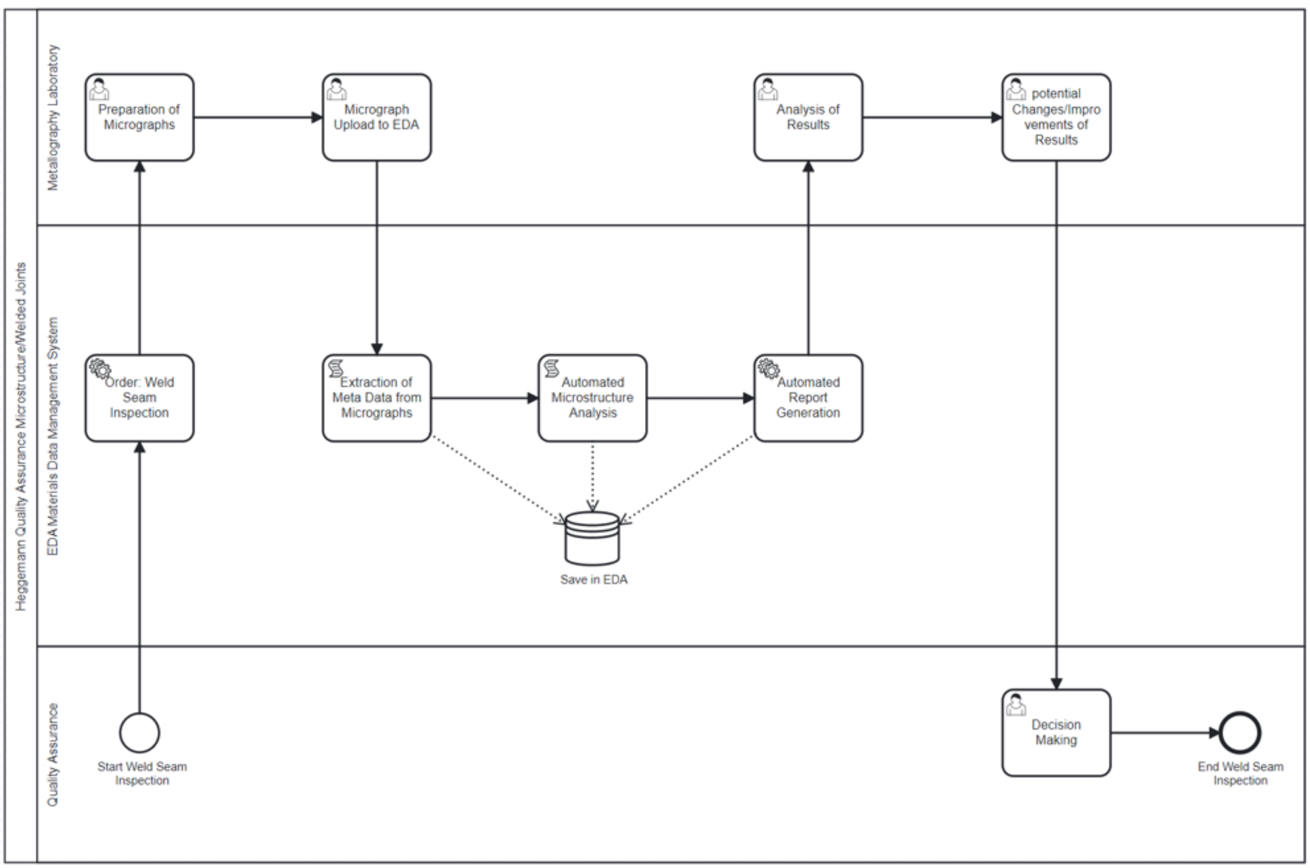

Fig. 3 - Electronic workflow for the inspection of weld seams from the DAF project

The workflow spans three lanes: quality assurance, the materials management system, and the metallographic lab. Quality assurance initiates the weld seam inspection and makes the final decision. The materials management system automatically generates the inspection order, runs the microstructure analysis, and provides a report. The lab prepares micrographs, uploads them to the system, and reviews the auto-generated report with the option to adjust or refine the analysis manually.

6. Conclusion:

Digitalization is essential for advancing materials engineering and optimizing processes across the steel industry. A unified infrastructure that integrates material behavior, process history, and traceability provides a scalable, standards-compliant foundation to address technological and workforce challenges. At its core is a graph-based architecture that enables end-to-end tracking of material property evolution, enhanced by visual modeling tools, automated workflows, and CAE-ready material cards. Demonstrated through the manufacturing of a WAAM-produced steel component, including heat treatment and machining, the system supports data-driven decisions, accelerates innovation, and ensures consistency across the entire value chain.

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