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# PARAMETRIZATION OF A HYBRID COMPONENT PRODUCTION PROCESS CHAIN BASED ON SEMANTICALLY ANNOTATED DATA

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**Abstract:** *The development of a novel manufacturing process chain is a complex scientific challenge and requires interdisciplinary collaboration, as well as technological solutions that extend the boundaries of automation and customize the information flows between different organizational units. Due to these challenges an approach to parametrize each step in the production chain and its careful documentation must be considered. This publication describes an approach to provide seamless digital access to sample and process-related data through semantic annotation. In this way, it can be traced how and with which process layouts of the individual process steps a sample was manufactured along the process chain. The implementation of the approach is shown in the example of a novel process chain for the production of multi-material bearing washers within the Collaborative Research Center (CRC) 1153. A workflow based on a semantic annotation using a domain-specific vocabulary is presented, which allows to obtain the necessary process parameter values according to the individual requirements of the multi-material component.*

**Key Words:** ***Human Machine Interaction, Semantic Annotation, Knowledge Management System, Process Monitoring***

## 1. INTRODUCTION

When developing novel process chains, scientists are confronted with a multitude of unknown influences of the individual process steps. Meeting the given requirements entails an iterative process in process design. The knowledge about the applied production processes is considered the cornerstone to ensuring constant high product quality. The use of new technological solutions can extend the boundaries of automation and customize the information flows between different organizational units. In collaborative projects, researchers from various sub-disciplines work together on a mutual research problem in different projects [1]. Thereby different projects generate, process, and analyze data using a variety of procedures and methods [2]. The efficient management of data and information, generated in research processes, and the acquisition of knowledge is a critical success factor for large, collaborative projects [3] To provide the foundation for possible process individualizations and, thus customization of the final product or solution, an approach to parametrize each step in the production chain and its careful documentation must be considered, at an early stage of research within the process chain [4].

Thus, new process parameter combinations can be repeatedly selected within the individual process steps to optimize processes and gain new knowledge [5]. During a process step, many different parameter configurations should be identified and investigated during process execution [6]. The individual processes should be protocolled and contain data on the corresponding experiment. This data must be continuously exchanged between the researchers involved to coordinate the individual process steps and determine cause-effect relationships within the process in Collaborative Interdisciplinary Research Projects [7].

This paper presents the design and implementation of semantic annotations for the documentation of experiments of a production process step along a process chain in a Research Data Management System (RDMS). Semantic annotation means the addition of defined metadata, through which the process steps along a process chain are described in machine-readable form, and thus information is linked with each other in order to generate new knowledge [8]. The aim of this approach is a formal documentation of the processes by means of protocols and their linkage along a real process chain. In this way, knowledge and defects that occur during production can be traced back to an entire process chain. The implementation of the approach is shown in the example of a novel process chain for the production of multi-material bearing washers within the Collaborative

Research Center 1153 “Process chain for the production of hybrid high-performance components through tailored forming” [9]. An internal Knowledge Management System (KMS) based on a semantic annotation using a domain-specific vocabulary is presented, which allows obtaining the necessary process parameter values according to the individual requirements of the investigated multi-material component. In section 2 the background of the tailored forming specific process chain of a selected demonstrator and the knowledge management system for the research data management is described. Section 3 is dedicated to the use case in detail, starting with the system requirements from the users’ and developers’ perspectives, the identification and creation of the entities for semantic annotation, and the implementation of the created semantic into the system to enable the researchers to document their research processes. In addition, an exemplary benefit of the system is presented in the form of a query. Section 4, summarizes the created knowledge space for the Research Data Management (RDM) by using semantic annotation.

## 2. BACKGROUND

This section gives firstly a short introduction to the concept of a hybrid component demonstrator manufactured by tailored forming and presents the applied novel manufacturing process chain specific to this technology. Using one of the process chains for manufacturing a demonstrator, the requirements for a formal and machine-understandable process description in interdisciplinary and interorganizational collaborations are outlined.

Subsequently, the main characteristics of a knowledge management system for the research data management are presented in order to manage contextual data or information that accrues for the process description.

### 2.1. Tailored forming specific production process chain

In the CRC1153, novel tailored forming-specific process chains are being investigated, to manufacture hybrid solid components with locally adapted properties through the targeted use of different materials within a component [10]. Therefore, several different process steps are combined with the aim of manufacturing hybrid components with local-adopted properties by using different materials [11]. Due to the number of necessary process steps, the complexity of the corresponding process chain is high [4], which results in further challenges with regard to the reliability of the whole manufacturing process. Here, the manufacturing process chain of a hybrid bearing washer is presented as an example (see Fig. 1):

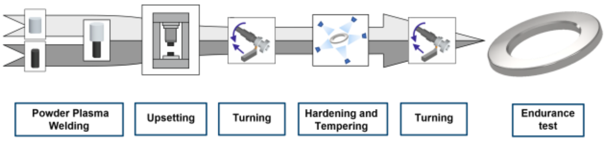


Fig. 1. *Process Chain of a Multi-Material bearing washer produced by Tailored Forming*

In the first step, wear resistant steel is sequentially welded onto a construction steel blank by power plasma welding to produce a hybrid semi-finished workpiece. In the following upsetting process, the workpiece is heated and formed into the hybrid bearing washer, which is then subjected to turning and, subsequently, to induction hardening. The last step is the hard turning of the bearing washers to the final geometry. In the end, an endurance test is carried out with the manufactured products. [12]

Within such a process chain, each process step and the determination of parameters is carried out by a responsible subproject. To coordinate the process steps collaboratively and to develop the process chain as a whole, the process information must be exchanged bidirectionally, since the individual process steps interact with each other and previous process steps influence the realization of the following process steps [13]. This fact underlines the importance of a formal and comprehensible process description, which is made accessible across all subprojects within the development of novel process chains. Since most of the process documentation is subproject specific and not made accessible to other subprojects, as well as not placed in relation to the individual process steps when considering an entire process chain, there is a risk of consequential effects and synergies not being identified.

### 2.2. Knowledge Management System (KMS)

The KMS is one part of the designated Research Data Management System (RDMS) in the CRC. The KMS addresses all information associated with the process description. New process chains are being researched in the CRC to drive the development of tailored forming technology. Descriptive data plays an important role in the development of process chains. Descriptive data refers, for example, to the setting parameters of machines and tools used in various process steps and is thus important metadata for documenting research data generation. The contextualization of research data generation is recorded in protocols of experiments, tests, measurements, or simulations. These documents contain detailed information about the samples and methods used, as well as the executive scientist, on what day, and with what machines and tools. Protocols thus provide all the contextual data and information needed to fully understand the idea for an experiment, its design, how it was conducted, the data collected, and how it was interpreted. This content is stored in the KMS implemented in the CRC. Entity linking, however, is not limited to a single experiment. In the CRC, interconnected steps within process chains that interact with each other are studied. Identifying hidden dependencies and correlations between experimental conditions of these process steps offers huge potential to increase the efficiency of the manufacturing process. Semantic linking of entities and protocols in the KMS enables the creation of a knowledge space for a given research question.

The KMS captures the description of entities related to research activities like protocols, samples, processes, machines, and tools. The KMS is developed based on Semantic MediaWiki (SMW) [14] and enables contextualizing, storing as well as maintaining unstructured data and information in a structured way using machine-interpretable semantics [15, 16]. Samples, protocols, machines, and tools are entered into the KMS by applying normalized templates which use the controlled vocabulary in the background.

## 3. DOCUMENTATION OF EXPERIMENTAL PROTOCOLS OF PROCESS STEPS IN A PROCESS CHAIN

### 3.1. Identification of researchers' requirements

Within the subprojects, the researchers perform various production steps that are realized by different manufacturing processes. The documentation of these experiments follows different process-related parameters. For all manufacturing steps carried out in the CRC, the relevant parameters must be recorded in expert interviews with the responding researchers which execute the processes for the formal representation of input- and output- and device parameters and prepared in the form of protocol templates. This enables uniform documentation on the part of the scientists for the various process steps. The parameters defined in this way within a defined manufacturing step can be used to make individual process executions comparable. In addition, it is relevant to be able to subsequently trace the various production steps with which a sample was manufactured. For this reason, it must be possible to map the individual production steps in the form of a process chain in the KMS. In this way, the process chains for producing samples can be reconstructed and compared. In this way, the process chains for the production of samples can be reconstructed and compared.

To keep a full overview of the experiments performed, the researchers face major challenges:

Creating Samples:

The samples are the main object of interaction when it comes to tracing which process steps a sample has undergone and which experiments have been carried out with the sample. Important characteristics for the description of the samples in the SMW are the unique sample ID with which a sample can be uniquely identified, the material combination of which the sample is made, the demonstrator geometry of the components manufactured, the batch number, and by which subproject and researcher the sample was created.

Detailed documentation of the experiments:

Firstly, it is important to document such general information as the date and time of the experiment, responsible person, corresponding subproject, and affiliation of the sample to enable other researchers in the CRC to make contact in case of questions. Secondly, the information about applied machines and tools, if applicable, their combination, as well as a complete set of their setting parameters, shall be included in the description of the experiment, so that one or more process results can be compared to each other to identify a possible cause of failure or conditions for the best result. Thirdly, a detailed documentation of the process with defined parameters, regarding the input and output characteristics of a Sample or other process-related parameters is necessary.

Sample Monitoring:

To be able to trace how a sample was manufactured along a process chain, the individual protocols documenting the individual process steps must be displayed coherently. For this purpose, it must be clear which protocols are linked to the sample. In addition, the chronological order of the associated process steps must be recognizable, as well as the current location of the sample. For this purpose, it must be documented when, where, and to whom a sample was transferred. In practice, this is usually done by passing on protocols, which must be digitized. In this way, the documentation results of a specific sample can be traced centrally and chronologically.

Accessibility of experiments' documentation and results for all CRC members:

The production of semi-finished workpieces applying the tailored forming technology generally runs in a process chain of different process steps. Thus, the information about all experiments performed shall be traceable for all CRC members involved to enable a more time- and resource-efficient process design. To meet the researchers' needs for the protocol documentation, the following requirements are identified in order to create an appropriate semantic annotation:

R1: The protocol structure shall be universal to enable reuse for the documentation of other experiment types within the CRC;
R2: The protocol for a given process has defined parameters to describe the process;
R2: Entities that represent samples, projects, protocols, and devices shall be semantically interlinked;
R3: The protocol shall visualize the general characteristics of the samples assigned to this protocol;
R4: Machines and tools are linked to the protocols of a specific process including specific properties in which they are used;
R5: A sample page visualizes the given transfers of the samples and applied Protocols to be able to trace the process chain of a sample.

### 3.2. Creation of semantic entities

When developing semantic annotation first the key research artifacts appropriate for a specific process are identified and the relevant categories are created: *Samples, Protocols, Projects, Devices, and Control Sheet*. Hereby, the Device category is divided into Machines, which can be used independently to realize a specific function, and Tools, which can not act or be used independently and needs to be combined with a machine. This allows the researchers to document the same experiment repeated several times using one machine in combination with different tools.

In order to realize individual wiki pages represented by *individuals* of the given categories unambiguously, several kinds of unique identifiers are created: The Sample Unique Identifiers are built as a combination of an identification letter of the respective subproject, for example, the letter "A" representing the subproject A1, and a four-digit number starting with 0000, e.g. "*A0001*".

The Unique Protocol Identifiers are complex letter-number combinations, e.g. "*PA4PPW0000*". The "*P*" stands for a protocol, "*A4*" for the subproject, and "*PPW*" for a defined process acronym in this case for Power

Plasma Welding. The four-digit number enables an unambiguous differentiation of individual protocols.

Machines have a complex string for their name that consists of three elements separated by space: machine name, type designation, and manufacturer name, e.g. “*Plasma power source Kjellberg Finsterwalde PSI 400*”. Using such complex designation is needed to differentiate similar machines from each other because more than one machine of the same type and manufacturer is included in the KMS. The Projects are represented via internal subproject designation, e.g. Project A1.

Next, properties specifying identified categories are created. The category *Samples* is characterized by the properties *HasUniqueSampleIdentifier, RepresentsDemonstrator, HasBatchNumber,* and *HasMaterialCombination*. The sample is then always used in the following as a recognition feature to present the documentation in the SMW sample-oriented.

To be able to trace each transfer of a sample and thus reconstruct the corresponding process chain in which a sample was manufactured, there is the *Control Sheet* category. This category contains the property *UniqueIdentifier* for every *individual* and refers to a sample with the property *HasUniqueSampleIdentifier*. In addition, the category has the subobject *Transfer Step* for each sample transfer made. The subobject has the properties, *DateOfTransfer, HasUniqueIdentifier, GivenByPerson, ReceivedByPerson, GivenByProject,* and *ReceivedByProjec*t. The values of the last two properties are specified as pages, which allows redirection to the relevant subprojects.

The category *Device* is characterized using two property sets: The first property set involves generalized properties applying to all machine types specified within the KMS: *HasPhysicalLocation, HasManufacturer, HasType, HasImage, UsedBySubproject,* and *UsedByProtocolType*. The values of the two last are specified as pages, which allow redirection to the relevant sub-project and protocol pages. The second property set is only valid for the machine-specific settings, for example for the above named machine used in the powder plasma welding process [17]: *CurrentRange, AppliedWeldingTime, AppliedFeedRateOfPowder,* and more. Here, standardized designations [18] are used to avoid possible misunderstandings between researchers.

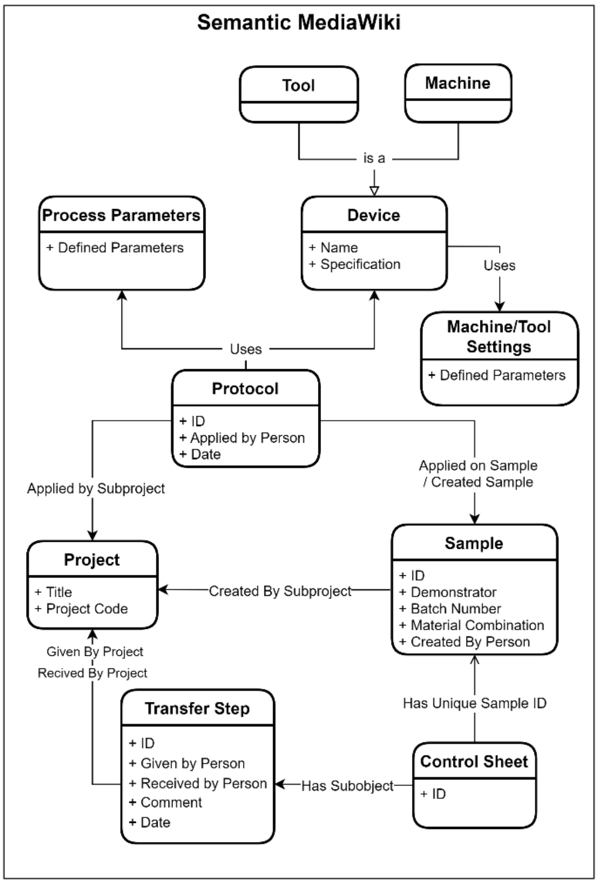


Fig. 2. *Entities and their Relations of the SMW structure*

The category *Protocol* is specified using the set of properties *HasDate, AppliedByPerson, CreatedSample/AppliedSample,* and *AppliedBySubproject*. The last two properties are assigned pages for the values that allow redirection to the pages of the linked sample and subproject. The associated process parameters, with which a specific process is formally and unambiguously described, are further properties of the category. Just like the settings of the machines, which are reflected in the protocols, these parameters are also recorded by expert interviews with the responsible scientists which execute the processes and thus reflect the requirements for recording their processes. These are property sets for the process-specific input and output workpiece characteristics or more process-specific parameters to describe the given experiment. For example for the powder plasma welding process, there are two more property sets. One property set is the input workpiece characteristics: *HasLength, HasDiameter,* and *HasThickness.* Furthermore, there is a property set for information on the used filler material: *ProducedByGasAutomization, HasAlloy, HasGrade,* and *HasParticleShape.* Since the described powder plasma welding process is the initial process of the process chain, the samples in the form of hybrid semi-finished workpieces are created in this step. Therefore, this process has only the input workpiece characteristics, which describe the generated sample out of two different materials. The following process steps have in most cases both input and output workpiece characteristics for their description.

After the category descriptions have been completed, the appropriate templates and forms are created for them. The Protocol and Sample relevant entities, their relations, and their interlinking are illustrated in (Fig. 2). This structure is further used to build a complex protocol template for a specific protocol in SMW.

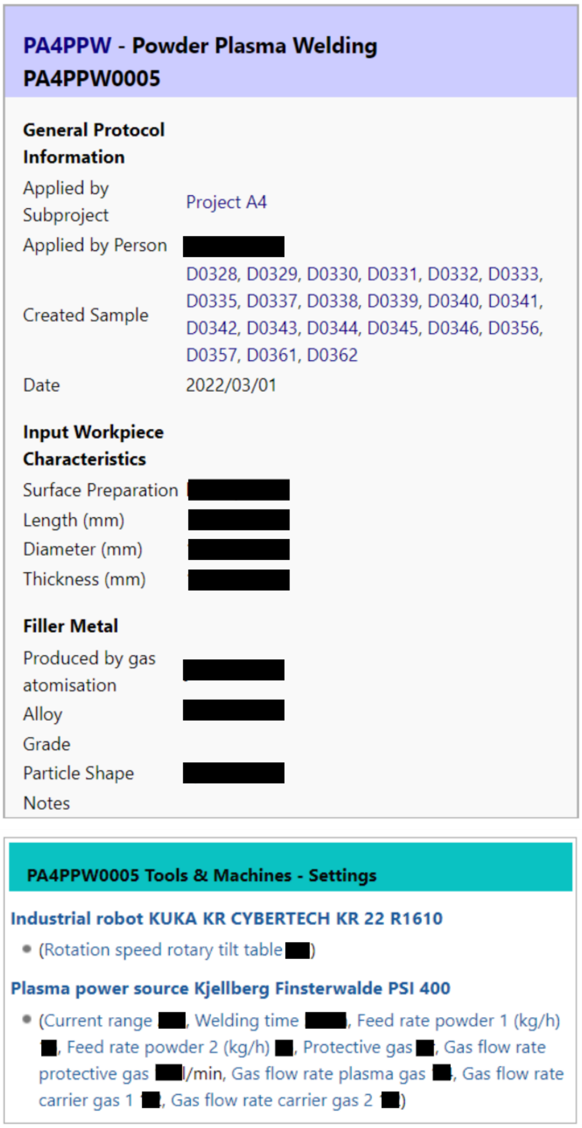
### 3.3. Representation of a protocol and sample transfer in Semantic MediaWiki

Considering the requirements from 3.1, the needed protocol and sample transfer structures are realized as an SMW page with several embedded templates including templates of the above categories for a protocol of powder plasma welding process (see Fig. 3) and for a given sample transfer of a specific sample (see Fig. 4).

In addition to general information, the different protocol types have further parameters in the form of properties that are assigned to the protocols, depending on the process they are documenting. The parameters defined by expert interviews are implemented in corresponding templates, which are queried when a process is protocolled. Thus a certain protocol type possesses a defined set of parameters, with which the process is described. The parameters depend on the one hand on the machines that were used in the process and on the other hand on process-specifics of the manufacturing method used and the workpiece characteristics. Specific templates for the various protocol types ensure that only the parameters determined as relevant are queried for the protocol. These different categories are visualized as separate sections on the protocol page.

The first section is divided into general protocol information and process-specific process parameters. The general protocol information is based on the template combining a set of protocol-related administrative properties mentioned in 3.2. The query of the process-specific parameters while creating a protocol is based on another template where the parameters are linked to the protocol type of the process and are queried.

The second section, Machines&Tools-Settings, is created through the integration of a complex machine-related template. It incorporates the first axillary template, whereby setting parameters are associated with the machine used within the process procedure, and the second auxiliary template, which uses a query and allows these setting parameters to be visualized on the protocol page, once the relevant machine is selected.



**PA4PPW - Powder Plasma Welding**
**PA4PPW0005**

**General Protocol Information**

| | |
|---|---|
| Applied by Subproject | Project A4 |
| Applied by Person | [redacted] |
| Created Sample | D0328, D0329, D0330, D0331, D0332, D0333, D0335, D0337, D0338, D0339, D0340, D0341, D0342, D0343, D0344, D0345, D0346, D0356, D0357, D0361, D0362 |
| Date | 2022/03/01 |

**Input Workpiece Characteristics**

| | |
|---|---|
| Surface Preparation | [redacted] |
| Length (mm) | [redacted] |
| Diameter (mm) | [redacted] |
| Thickness (mm) | [redacted] |

**Filler Metal**

| | |
|---|---|
| Produced by gas atomisation | [redacted] |
| Alloy | [redacted] |
| Grade | |
| Particle Shape | [redacted] |
| Notes | |

**PA4PPW0005 Tools & Machines - Settings**

**Industrial robot KUKA KR CYBERTECH KR 22 R1610**

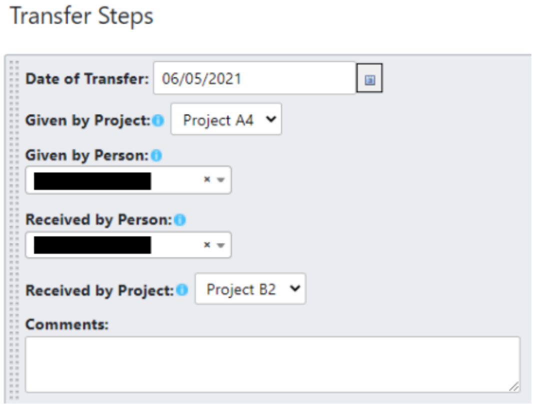
- (Rotation speed rotary tilt table [redacted])

**Plasma power source Kjellberg Finsterwalde PSI 400**

- (Current range [redacted], Welding time [redacted], Feed rate powder 1 (kg/h) [redacted], Feed rate powder 2 (kg/h) [redacted], Protective gas [redacted], Gas flow rate protective gas [redacted]l/min, Gas flow rate plasma gas [redacted], Gas flow rate carrier gas 1 [redacted], Gas flow rate carrier gas 2 [redacted])

Fig. 3. *Visualization of a protocol in SMW*

The documentation of sample transfers is based on a defined template, which contains the properties of the described category mentioned in 3.2. The template for the sample transfer is called up via the samples page since the information on the sample transfer is sample-specific. Thus, it can be specified when a sample is transferred to a next subproject for further processing and where the sample is at the current time.



Transfer Steps

**Date of Transfer:** 06/05/2021

**Given by Project:** Project A4

**Given by Person:** [redacted]

**Received by Person:** [redacted]

**Received by Project:** Project B2

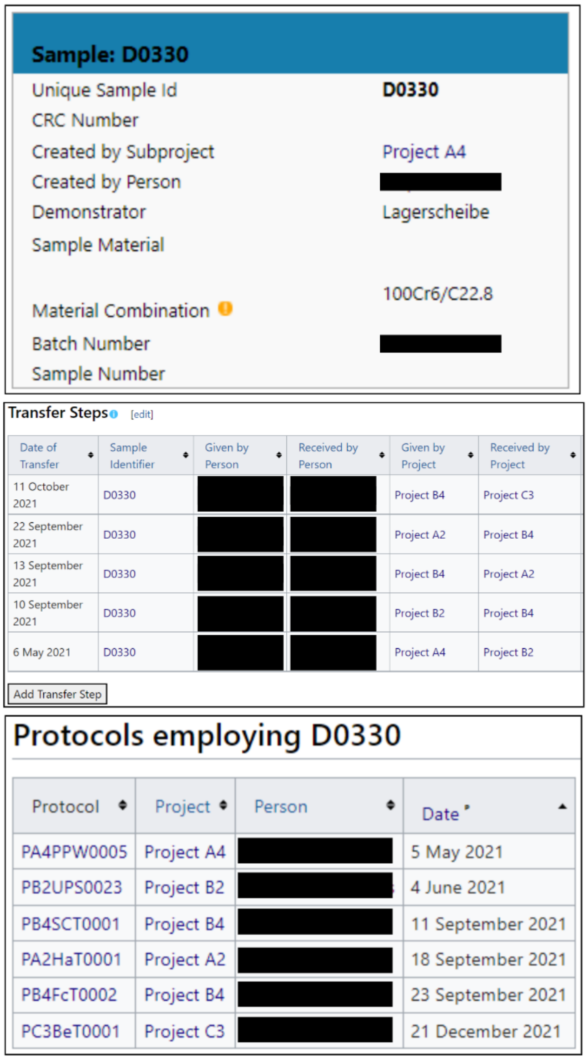
**Comments:**

Fig. 4. *Template a transfer step in SMW*

The sample transfer of a sample makes it possible to trace and reconstruct the process chain in which a sample was processed. The visualization of all transfer steps of a specific sample are then displayed on the specific sample page (see Fig. 5)

### 3.4. Representing of a Sample in Semantic MediaWiki

On the sample page of a particular sample, all information is clearly displayed based on the described semantics (see Fig. 5). The overview concerns all protocols and sample transfers that refer to the specific sample ID.



**Sample: D0330**

| | |
|---|---|
| Unique Sample Id | **D0330** |
| CRC Number | |
| Created by Subproject | Project A4 |
| Created by Person | [redacted] |
| Demonstrator | Lagerscheibe |
| Sample Material | |
| Material Combination | 100Cr6/C22.8 |
| Batch Number | [redacted] |
| Sample Number | |

**Transfer Steps** [edit]

| Date of Transfer | Sample Identifier | Given by Person | Received by Person | Given by Project | Received by Project |
|---|---|---|---|---|---|
| 11 October 2021 | D0330 | [redacted] | [redacted] | Project B4 | Project C3 |
| 22 September 2021 | D0330 | [redacted] | [redacted] | Project A2 | Project B4 |
| 13 September 2021 | D0330 | [redacted] | [redacted] | Project B4 | Project A2 |
| 10 September 2021 | D0330 | [redacted] | [redacted] | Project B2 | Project B4 |
| 6 May 2021 | D0330 | [redacted] | [redacted] | Project A4 | Project B2 |

**Protocols employing D0330**

| Protocol | Project | Person | Date |
|---|---|---|---|
| PA4PPW0005 | Project A4 | [redacted] | 5 May 2021 |
| PB2UPS0023 | Project B2 | [redacted] | 4 June 2021 |
| PB4SCT0001 | Project B4 | [redacted] | 11 September 2021 |
| PA2HaT0001 | Project A2 | [redacted] | 18 September 2021 |
| PB4FcT0002 | Project B4 | [redacted] | 23 September 2021 |
| PC3BeT0001 | Project C3 | [redacted] | 21 December 2021 |

Fig. 5. *Visualization of a sample page in SMW*

The first section contains general information about the sample and is based on the sample creation template with the corresponding properties as described in chapter 3.2.

The second section gives an overview of the sample transfers that have taken place in the form of the transfer steps described in the previous chapter. On the sample page, the chronological order of the given transfer step is displayed. This visualization is based on a sample transfer-related template, that is built using a query calling the information stored on a sample-related individual control sheet page.

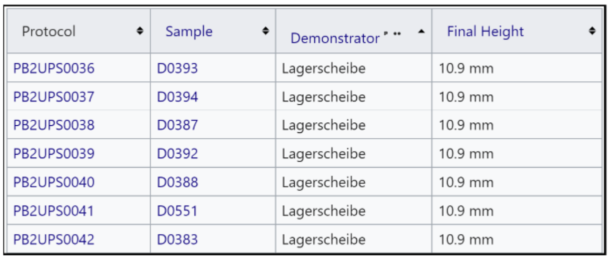
In this way, the history of the sample can be traced and where it is currently located. The history of the sample with the associated logs can then be used to reconstruct and trace the process chain.

The third section shows all protocols of processes that are applied to the specific samples and is based on a protocol-related template, that is built using a query calling the information stored on an individual protocol page. The unique protocol identifiers are specified as a page, with which one can directly access the corresponding protocol. In this way, an overview of the individual process steps is obtained in the form of the protocol. As described in the previous chapter, the individual process steps are formally described by defined parameters in the protocols.

Each created sample has its own page in the SMW and is built according to the described structure and contains all information linked to the respective sample. Starting from the sample page, it is possible to call up the linked protocols and also individual subproject pages that are linked to the protocols or sample transfer.

### 3.5. Benefits obtained from the described semantic structure

The advantages of the described protocol structure and semantically annotated content can be illustrated by means of a parameter configuration request in the form of a query. Thus, protocols can be queried for specific parameter values and annotated data can be returned. An example competency question is, ”*Which samples of the bearing washer (de: Lagerscheibe) had a final height of the desired 10.9 mm after upsetting?*”. The final height of the samples after upsetting is a defined parameter with the property *FinalHeight* in the protocol types for upsetting. Applying this query, the following results are received (see Fig. 6.):



| Protocol | Sample | Demonstrator | Final Height |
|---|---|---|---|
| PB2UPS0036 | D0393 | Lagerscheibe | 10.9 mm |
| PB2UPS0037 | D0394 | Lagerscheibe | 10.9 mm |
| PB2UPS0038 | D0387 | Lagerscheibe | 10.9 mm |
| PB2UPS0039 | D0392 | Lagerscheibe | 10.9 mm |
| PB2UPS0040 | D0388 | Lagerscheibe | 10.9 mm |
| PB2UPS0041 | D0551 | Lagerscheibe | 10.9 mm |
| PB2UPS0042 | D0383 | Lagerscheibe | 10.9 mm |

Fig. 6. *Visualization of an excerpt of the query result*

Due to the formal description of the processes described at the beginning, all samples can be identified by the query, which have the corresponding height after the upsetting process. The result is displayed in a table with links to the corresponding sample pages.

Further, the other processes of these samples can be examined and process descriptions of associated life analyses can be viewed through the corresponding protocols in order to identify possible influences of the height of the bearing washer after the upsetting on the operating life.

The search results presented above show one possible use case for retrieving process parameters.

Since the internal KMS is accessible to all CRC members, the log documentation and data query functions are open.

Thus, depending on the application, any other queries can be performed.

## 4. CONCLUSION

The work presented in this paper describes a KMS for the formal parametrized description of processes up to the linkage to process chains as one solution for the research data management. With the described system, the handling of contextual information in the form of samples, protocols, and sample transfers within the CRC is represented. The semantic annotation of these research artifacts enables their connection across the system, thus providing a comprehensive understanding of the processes realized in the CRC. The query carried out shows the benefits that can be derived from the system and that a formal description of the processes through parameter specifications can promote the development of new process chains. In this way, process steps can be made comparable and placed in the context of an entire process chain. The specific use case of a given process chain in the Tailored Forming Technology can be generalized and mapped to other research domains concerning process description and process executions. By now, the structure of samples, protocols, tools, and machines has been applied successfully in another collaborative project [19, 20] for the integration of a digital machine park and a measurement request system into an RDMS. Although parts of the semantic annotation for the different protocols are very specific, one can see that the structure remains very flexible. It can be modified by adding or removing entities to make the protocol suitable for other applications. In the future, the addition, semantic annotation, and linking of further research artifacts in the RDMS are planned.

## ACKNOWLEDGMENTS

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