Ontology-based Documentation of Quality Assurance Measures Using the Example of a Visual Inspection

Tatyana Sheveleva[1[0000-0002-2125-0872]], Kevin Herrmann[2[0000-0001-7089-6322]], Max Leo Wawer[2[0000-0003-3806-271X]], Christoph Kahra[3[0000-0002-0048-1655]], Florian Nürnberger[3[0000-0002-7824-0675]], Oliver Koepler[1[0000-0003-3385-4232]], Iryna Mozgova[2[0000-0002-6761-0220]], Roland Lachmayer[2[0000-0002-3181-6323]], Sören Auer[1[0000-0002-0698-2864]]

[1] Leibniz Information Centre for Science and Technology (TIB), Welfengarten 1B, 30167 Hannover, Germany

[2] Institute of Product Development, Leibniz University Hannover, An der Universität 1, 30823 Garbsen, Germany

[3] Institut für Werkstoffkunde (Materials Science), Leibniz Universität Hannover, An der Universität 2, 30823, Garbsen, Germany

Abstract. The development of a novel manufacturing process chain is a complex scientific challenge and requires interdisciplinary and inter-institutional collaboration. Data need to be exchanged continuously between involved researchers in order to coordinate between individual process steps and to identify cause-effect relationships within the process. This publication describes an approach to provide seamless digital access to quality-related data and to further structure, semantically annotate and link process- and quality-relevant data. It uses a domain-specific ontology called Visual Inspection Ontology embedded in a Knowledge Management System to support the documentation of a quality-determining process. The ontology is applied to a use case from the development of a novel process chain to manufacture multi-material shafts within the Collaborative Research Centre (CRC) 1153. A workflow to establish quality control measures regarding a novel process chain for multi-material high-performance components under development based on the proposed ontology is presented.

Keywords: Human Machine Interaction, Semantic Annotation, Knowledge Management System, Sample Monitoring, Tailored Forming.

1 Introduction

The ability to produce high-performance components at low-costs is a major factor when estimating the economic performance of a manufacturing company. The knowledge about the applied production processes is considered the cornerstone to ensure constantly high product quality. The use of new technologies is supporting this cause by enabling a constant acquisition of process data. Data mining methods complement the acquisition by implementing a real time analysis of the data and subsequently implementing a control system for the process. In general, this process control demands three requirements:

1. The process needs to meet the specified customer requirements [1];
2. The process parameter window resulting in the production of high quality products needs to be known; and
3. The process needs to be controlled; I. e. the process behaviour is predictable.

Process chains using known manufacturing technologies usually meet these requirements. However, they are not or only partially met within research projects developing novel production processes and technologies. The technologies used in individual process steps under development are not yet sufficiently identified, matured, and stable to guarantee the consistent quality of the manufactured components. Furthermore, the interdependencies between several process steps within a process chain are usually also unknown. The incomplete knowledge and understanding of each process step results in the inability to predict the effect of a change in a prior step on further processes. Therefore, the development of a novel process chain is considered an iterative process adapting each production step several times and examining the effect of changes throughout the whole chain. To this mean, the collaboration of experts from different disciplines is required. The successful development of a process chain is therefore depending on an optimal data flow between the individual processes [2, 3].

The design of novel manufacturing process chains using Tailored Forming Technology is the subject of the Collaborative Research Centre (CRC) 1153, where various production methods for different types of component are being investigated in various subprojects. Each subproject generates a large amount of data [4], which, when examined together, forms the basis for a cross-process quality management of a process chain.

This publication presents an approach for supporting quality-assured measures within an internal Knowledge Management System (KMS) using a domain-specific ontology. As a use case serves a visual inspection performed before and after a specific manufacturing process.

2 Background

This section gives a short introduction to the concept of Tailored Forming and presents a novel manufacturing process chain specific to this technology. Using one of the process steps as an example, the current challenges of introducing quality assurance measures within the CRC 1153 are outlined.

2.1 Tailored-Forming and its Specific Manufacturing Process Chain

In CRC 1153, novel Tailored Forming-specific process chains are being investigated [5]. Hereby, several different processes are connected in series with the aim of manufacturing hybrid components with local-adopted properties by using different materials [6]. Due to a high number of necessary process steps, the complexity of the corresponding process chain is increased [7], which results in further challenges with regard to the reliability of the whole manufacturing process. Here, the manufacturing process chain of a hybrid shaft is presented as an example (see Fig. 1):

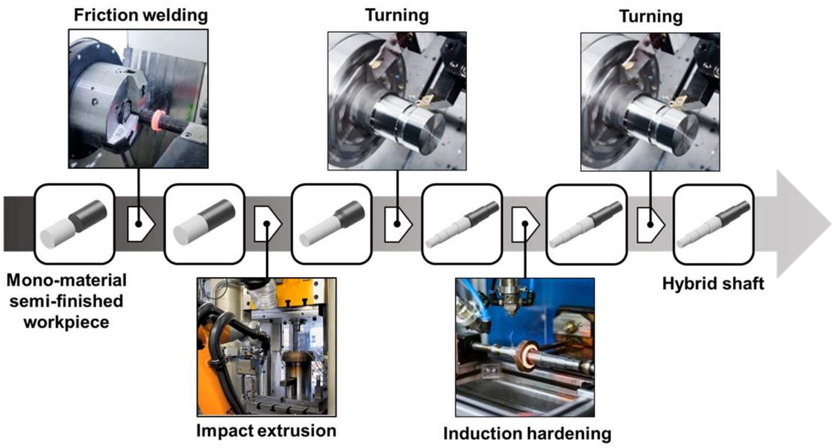

Fig. 1. Process Chain for the Manufacturing of a Multi-Material Shaft by Tailored Forming

In the first step, two mono-material workpieces made of steel and aluminium are joined sequentially by friction welding to a hybrid semi-finished workpiece. In the following impact extrusion, the workpiece is inductively heated and preformed to the hybrid shaft, which is then subjected to turning and, subsequently, to induction hardening. The last step is the turning of the shaft preform to the final geometry.

Within such a process chain, each process step and its parameters are determined by a responsible sub-project. In order to coordinate the process steps collaboratively and to develop the process chain as a whole, data must be exchanged bidirectionally, since the individual process steps interact with each other and a level of quality of the upstream step is necessary to perform the subsequent steps successfully. This fact underlines the importance of quality assurance measures and makes their establishment indispensable within the development of novel process chains. While quality control is usually used in established methods and seems to be a stretch for production research, there is a threat of deficiencies and pitfalls without such a system in place.

2.2 Status Quo of Quality Assurance Measures in the Given Use Case

Within the CRC 1153, various quality assurance measures are currently being used and further introduced individually by each subproject. These consider structured data, e. g. temperature, and geometry measurement as well as unstructured data, e. g. documentation of the processes, like visual inspection.

Visual inspection is performed twice during the transfer of the workpiece between the subprojects: once as output inspection from the giving subproject, focusing on workpiece characteristics for the own process and is optionally supported by structured as well as quantitative measurements. A non-standardized rating of the workpiece quality is usually documented in a hard copy control sheet attached to this workpiece when it is handed over to the next project. Furthermore, the workpiece is visually inspected by the receiving projects and evaluated by its suitability for its own process. The inspection by giving and receiving projects may cover different features and the inspection results may or may not be transferred to the other subproject in a suitable data format.

Within the example process step of heat treatment, a visual inspection is performed to inspect the form and the physical appearance of the workpiece. During the input visual inspection, only visible defects are identified, e. g., obvious form distortions, pores, or cracks. It is only used to check the essential geometrical compatibility of the workpiece to the tool environment and involves identifying intolerable form deviations, e. g. length or diameter differences. Any non-visible defects like joining errors are not detectable. The output inspection is applied both with the focus on the workpiece and on the process after the heat treatment. It involves a further visual inspection of the heat-treated workpiece to identify defects induced by heat treatment, e .g. an additional form distortion caused by different thermal expansion coefficients of the used materials. The analysis of the parameters employed in case of detecting faulty workpieces is a commonly used tool to identify critical parameters and relevant remedial actions. For the heat treatment use case, a workpiece distortion is stated as a reason for the failure of the inductive hardening.

Exceptional results of the inspection are noted as unstructured text on the control sheet on paper. Along the process chain, such a control sheet documents all process steps applied on the workpiece and by whom. Additionally, process-relevant information including a minimum description of the applied parameters is stored in a global sample registry, an Excel sheet on an FTP server. In some cases, data on workpieces are also forwarded by e-mail. In summary, several workflows are used to exchange data on the quality of workpieces between the subprojects. This way of working and the use of different media to pass on data about research objects are prone to errors and potentially incomplete. Not all subprojects have continuous access to quality-related data concerning their processes and the involved workpieces. This hampers the identification of cause-effect relationships within the process chain. Moreover, quality-related data is provided in different formats and in unstructured forms, which makes it impossible to search for complex data required for the use case. Based on such challenges, the following requirements have been identified in order to optimize the quality assurance measures making use of semantic annotation of the inspection-related data by the domain-specific ontology within the internal KMS:

1. VIOR1: The visual inspection shall be protocoled by using one medium providing the quality-related data in a structured form;
2. VIOR2: The protocoled visual inspection shall be accessible to all participating stakeholders;
3. VIOR3: The input and output visual inspections shall be protocoled separately;
4. VIOR4: The protocoled visual inspection shall provide the required data about associated samples, their defects, and persons responsible.

3 Ontology-Based Optimization of Quality Assurance Measures

The following section outlines the approach for the formal structuring of quality-related data using ontology and how it is applied within the internal knowledge management system to optimize the quality assurance measures of the heat treatment.

3.1 Design of the Visual Inspection Ontology

The potential enhancements described in section 2.2 are considered within the development of the structural basis for the visual inspection protocol, resulting in the so-called Visual Inspection Ontology (VIO). Additionally, more specific requirements have been identified in joint discussions with researchers performing the inspection. These requirements focus on retrieving specific information items that the VIO is supposed to provide and that result in the following competency questions:

- Which samples have been the subjects of the input/output visual inspection?
- What types of defects have been detected within the input/output visual inspection?
- Which samples examined the input/output visual inspection in the given time period have corrosion/offset/crack/fused area?

VIO have been created using the ontology editor Protegé (see Fig. 2). It imports case-relevant classes and properties from three different existing ontologies of a high abstraction level. So, the core upper classes and properties that are related to an observation are adopted from the Semantic Sensor Network Ontology (SSN) [8]. Due to their generalized meaning, the SSN entities form the basic skeleton of the VIO and build super-classes of the VIO-specific entities. Moreover, SSN entities serve as linking elements in the alignment of VIO with the further ontology of the highest abstraction level, the Basic Formal Ontology (BFO) [9]. Such interlinking with the BFO enables to connect VIO to further BFO-aligned ontologies if VIO is able to be applied in other research areas. A seamless alignment of the SSN to the BFO is ensured by the integration of the appropriate classes from the Provenance Ontology (PROV-O) [10]. Moreover, PROV-O enables further alignment with such metadata schemes like Dublin Core for the case that, e. g. person- or dataset-related data is to be semantically annotated in more detail.

The class vio:Visual Inspection, defined as a subclass of sosa:Observation stands for the quality-related inspection performed by prov:Person responsible. Representation of the inspection result is realized via the usage of properties sosa:resultTime and sosa:hasSimpleResult.

The class vio:Visual Inspection is expanded by two disjoint subclasses vio:Input Visual Inspection and vio:Output Visual Inspection, which stand for the two inspection types performed before and after the heat treatment. The vio:Sample, defined as a subclass of sosa:FutureOfInterest, represents a semi-finished workpiece undergoing visual inspection. The class vio:Defect represents the sample property, which is subject of the visual inspection, and is therefore defined as a subclass of sosa:ObservableProperty. Since the visual inspection is limited to detect defects without using any tools, only visible defects are considered. According to DIN 17022-2, the typical representatives of visible defects associated with heat treatment are corrosion, crack, fused area, and offset [11], which are included as subclasses of vio:Defect. However, this defect classification should not be considered complete as of now. Due to the novelty of the manufacturing technology with its high variety of the applied material combinations, workpiece geometry, and process settings, further types of defects may also occur. Once available, these have to be included into VIO subsequently to ensure a complete quality-related knowledge acquisition.

A defect is characterized by its location on the workpiece (vio:isLocatedInArea). Since location is not required to be determined quantitatively by specifying coordinates, the data type xsd:string is used instead. It allows the relevant data to be entered as free text without any limitation in content and value. The property vio:hasDefectStatus enables in turn to characterize the defect with respect to its significance for the quality of the heat treatment, like "critical" or "non-critical".

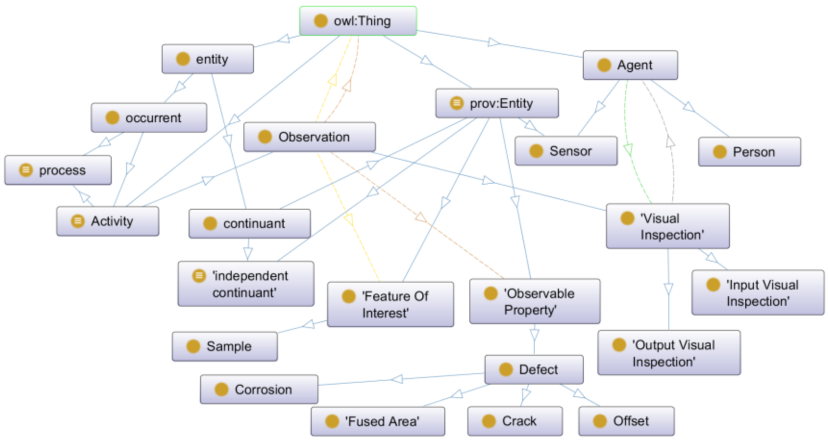

Fig. 2. Graphic representation of Visual Inspection Ontology by using Protegé's visualization plugin OntoGraf

Table 1. Data type properties graphically not shown.

Data Type Property	**Domain**	**Range**
vio:hasDefectStatus	vio:Defect	xsd:string
vio:isLocatedInArea	vio:Defect	xsd:string
sosa:resultTime	sosa:Observation	xsd:dateTime
sosa:hasSimpleResult	sosa:Observation	xsd:string

Table 2. Identification of object properties by color.

Object Property	**Arc Color**
has subclass*	
sosa:hasFeatureOfInterest	
sosa:observedProperty	
vio:made	
vio:madeBy	

*The property **has subclass** is created by OntoGraf automatically for visualization purposes and serves as the inverse of property **rdfs:subClassOf**

The developed VIO is available as a Turtle file at the GitHub repository TIB Onto via https://github.com/tibonto/vio. The structure of VIO serves as a knowledge base for the creation of protocols used for documentation of inspection results in the internal KMS of the CRC1153 and thereby contributes to the establishment of a centralized quality management.

3.2 Creation of Visual Inspection Protocols in the Knowledge Management System

The KMS of the CRC 1153 is based on Semantic MediaWiki (SMW) [12, 13], an open-source extension of the MediaWiki software [14]. It enables to collect, structure, and semantically annotate unstructured data by means of domain-specific vocabulary and thereby makes the data machine interpretable and searchable.

In the first step, the developed VIO structure is imported into SMW by using the extension ontology2smw [15]. The key entities of the VIO are used in the second step to build the structure of the visual inspection protocol to be presented as an SMW page. To realize this, a protocol template is created, whereby the classes and properties of the VIO are used as a knowledge resource. Here, the class vio:Visual Inspection is the subject of the protocol template. Other classes and properties serve in turn as its descriptive elements.

Within the template, VIO classes and properties are grouped in such a form, that they are visualized as separate sections representing specific content on the Wiki page (see Fig. 3). The first protocol section captures general administrative information about the visual inspection performed, e. g. inspection type (input or output), the responsible person, date of the inspection, the workpiece to be inspected, and inspection result. The second section is designated via the identification number of the initial inspection performed and the subject of the section content (observable properties standing for defects). It combines information about the identified defects and their characteristics, such as defect type, location, and status. This section is built on a query that calls the defect-relevant data after it is entered by the researcher into the system and displays it in table form. Despite the sectional splitting of the inspection-relevant data on the SMW page, both content elements are semantically interlinked with each other by being based on a common structure of VIO.

Visual Inspection 0001

Visual Inspection 0001 Observable Properties		
Observable Property	Is Located In Area	Defect Status
Corrosion Crack	top middle	critical non-critical

Visual Inspection 0001 - Output Visual Inspection	
Visual Inspection:	Output Visual Inspection
Made by:	
Result Time:	2020/08/04
Has Feature Of Interest:	G0001
Result:	failed
Notes:	

Fig. 3. Visual inspection protocol implemented in Semantic MediaWiki.

As a final outcome using such semantic annotation of the inspection-related data, the sample control sheets on paper can be completely replaced by the digital protocols available for all subprojects along the whole process chain.

3.3 Benefits Obtained from the Use of the Visual Inspection Ontology

The benefits of the usage of the VIO can be demonstrated by the translation of the following competency question into a query that is run using semantic search: "Which samples examined within the output visual inspection in the time period between 01.03.2020 and 18.11.2020 show corrosion and whether the corrosion is critical or non-critical? Additionally, the material combination of the relevant samples is to be displayed." Applying this query, the following results are received (see Fig. 4):

	Output Visual Inspection	Result Time	Sample	Material Combination	Defect	Defect Status
Visual Inspection 0001	Output Visual Inspection	4 August 2020	G0001	100Cr6/AW-6082	Corrosion Crack	critical non-critical
Visual Inspection 0002	Output Visual Inspection	11 March 2020	G0002	100Cr6/AW-6082	Corrosion	critical
Visual Inspection 0003	Output Visual Inspection	18 November 2020	G0006	100Cr6/AW-6082	Corrosion	non-critical
Visual Inspection 0012	Output Visual Inspection	5 August 2020	G0226	20MnCr5/AW-6082	Corrosion	non-critical
Visual Inspection 0016	Output Visual Inspection	5 August 2020	G0228	20MnCr5/AW-6082	Corrosion	non-critical
Visual Inspection 0017	Output Visual Inspection	6 August 2020	G0229	20MnCr5/AW-6082	Corrosion	non-critical
Visual Inspection 0018	Output Visual Inspection	5 August 2020	G0230	20MnCr5/AW-6082	Corrosion	non-critical
Visual Inspection 0021	Output Visual Inspection	6 August 2020	G0233	20MnCr5/AW-6082	Corrosion	non-critical
Visual Inspection 0027	Output Visual Inspection	6 August 2020	G0219	41Cr4/C22.8	Corrosion	non-critical

Fig. 4. Results of quality-related data retrieval obtained by using competency question "Which samples examined within the output visual inspection in the time period between 01.03.2020 and 18.11.2020 show corrosion and whether the corrosion is critical or non-critical? Additionally, the material combination of the relevant samples is to be displayed."

The query result is a table displaying a complete list of semi-finished workpieces in which corrosion has been identified after the heat treatment procedure. This information can be further used by the researchers, e. g. to identify the reason for the failure of the heat treatment procedure possibly caused by specific behavior of the used materials. Thereby, the blue marked column entries are provided as links redirecting to the relevant Wiki page. The black marked entries represent simple values, which do not have their own pages.

The search results presented above show only one possible use case for retrieving quality-related data, that is semantically annotated using VIO. Since the internal KMS is accessible for all CRC members, the functionality of protocol documentation and data retrieval are open as well, so that depending on the use case, any other queries can be performed.

4 Conclusion and outreach

The presented approach provides elements of comprehensive quality assurance measures within the development of novel manufacturing process chains in a large collaborative project by means of a use-case from the CRC 1153. First, all steps of the quality assurance measures have been digitized and embedded into a central Knowledge Management System based on Semantic MediaWiki, substituting former hard copy-based control sheets. By this means, visibility and accessibility of quality-related data has been significantly increased within CRC 1153. The digital mapping of control sheets has also improved the previously rather unstructured collection of data for quality assessment. The structured and standardized collection of statements on the quality of the semi-finished workpieces has been further improved by the implementation of the Visual Inspection Ontology into the internal Knowledge Management System. This enables a centralized documentation of the visual inspection procedures and their results as one quality assurance measure. Semantically annotation and linking of the inspection data from control sheets, heat treatment parameters, and workpiece characteristics enable in a next step the analysis of cause-effect relationships between parameters within processes and the quality of the workpiece.

The overarching availability of quality-determining process parameters broadens the perspective. Instead of optimizing a single process step and maximizing the quality of its outcome compared to the investment of resources, the perspective is planned to be extended to the whole process chain and the interaction of the sum of all process parameters identifying the most economic and highest-quality processing.

As a next step, a quantitative evaluation of the effects of the quality management of heat treatment is planned within CRC 1153. An extension of the Visual Inspection Ontology covering other quality inspection methods is ongoing work.

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