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On the tracking of individual workpieces in hot forging plants

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Tracking each workpiece provides two major advantages in forging technology. First, the matching of physical workpiece with the monitored process information facilitates root-cause analysis for product quality. Second, the following process steps can be adapted according to the incoming workpiece properties to improve the robustness of hot forging process chain. The paper presents a general tracking methodology and tagging experiments on aluminium and steel forgings for harsh drop-forging technology. Furthermore, a framework for streaming and processing large amounts of real-time data as well as a multidimensional approach to model and analyse the workpiece information for individual and batch-tracking are presented.

Forging, Digital Manufacturing System, Knowledge management

1. Introduction

The real-time networking of technical systems over digitalisation of products and processes is the revolutionary step in Industry 4.0. The fusion of virtual and real world with real-time data opens the way for real-time optimization of complex value-added systems based on the processing of measurement data and the forecast of future developments [1]. Analysis of big-measurement-data allows the determination of anomalies, correlations, patterns and constitutes the base for machine learning and adaptive-robust systems.

Hot forging is one of the technologies having a great potential of improvements in the spirit of Industry 4.0 [2]. The product quality and process stability are evaluated usually after forming or even after the heat treatment, based on properties of randomly selected products. The state-of-the-art application is the isolated digitalisation of individual processes and disassociated digitalisation of finished products. As a result, the cause of the scatter in the product properties cannot be linked with the individual process variables and parameter fluctuations. Efficient data communication within a forging system can only be achieved by back-tracking and linking online labelled measurements with physical workpiece, otherwise, correlations and patterns cannot be extracted. Furthermore, the reduction of the scrap rate by adaptive process parameters based on incoming material or part properties cannot be achieved.

Cannolly [3] has reviewed in 2005 the use of bar and matrix codes in assembly operations and for part tracking. Types of codes, marking methods and machine vision equipment are compared and the superiority of matrix code labelling is emphasized. Song et al. [4] developed a robust and accurate material tracking and locating solution for materials stored in large laydown yards. Proposed solution features barcoding and GPS-technologies for material tracking and fast retrieval in a cost effective manner. Dai et al. [5] investigated the tracking capability from the perspective of supply chain considering the tracking and recall costs in a supply chain with endogenous pricing. Denkena et al. [6] introduced a vibration assisted face milling technology enabling the machining of a matrix code or similar shapes into the component surface eliminating an additional marking step. Vedel-Smith et al. [7] developed a matrix code marking strategy for green sand castings where a flexible insert tool is used to emboss the mould itself before the melt is poured in. Montanini et al. [8] explored the possibilities of active infrared thermography in restoring covered and abraded marks obtained by laser, dot peen, impact, press and scribe marking on a steel surface. They reported on tested thermography techniques proved to be helpful in reducing local optical reflections and obtained enhanced readability with proper image processing of the raw images. The optical tracking of objects is an active research topic until now and can be applied too for tracking workpieces in the forging plants. Stolkin et al. [9] addressed the visual object tracking problem in extremely poor visibility conditions which could be transferred to forging environments. Akin et al. [10] introduced an effective DIC-based tracker with an improved deformable part-based model which tackles also scale changes in successive pictures. Kanagamalliga et al. [11] recently showed how background subtraction and feature extraction could be used to improve the visual tracking. He et al. [12] introduced an approach for spatio-tracking of moving objects using multiple cameras simultaneously. When applicable these DIC-based tools can be used to track workpieces eliminating the necessity of physical tags.

The common application of part marking in forging companies today depends usually on the size of workpiece and the production rate. Large workpieces with small production numbers are tracked by using labels, needling or marking. Small workpieces being manufactured in high production volumes do allow batch tracking. The ability to sample accurate process data and to correctly assign them to corresponding workpieces is a major challenge regarding the heterogeneity of data sources concerning data formats, protocols and sampling rates. Hence, software modules are needed that uniformly transfers the collected data from the machine level to a factory-cloud level storage. Modules should have an individual interface for each data source and a standardized interface to further the recorded data. Fundamentals of this concept are paved by Faul et al. [13].

The aim of this paper is on the one hand to formalise the know-how necessary for the workpiece tracking in forging plants using the state-of-the-art hardware and software techniques. On the other hand, a deep focus is put on further investigation of physical tags and data driven modelling of traceability. A successful workpiece tracking system needs robust tags *and* components wired with tracking software running at both machine and factory-cloud level. In this context, at first a general workpiece tracking methodology is developed and supported with multi-dimensional modelling of data-driven-traceability built on PLC-based data acquisition and processing. This methodology can be used to build a tailor-made tracking system. Second, practical tags appropriate for forging environment are investigated thoroughly and laser-engraving of QR-codes are performed onto the hot surface of forged aluminium and steel workpieces. Finally, an assistance system for a single/batch tracking is introduced.

2. Workpiece tracking methodology

A production line in a forging plant may consist of various processes depending on product itself and available infrastructure. This section introduces elements of a generalized methodology that can be tailored to a variety of production systems. Workpieces can be tracked on a batch level or individually. Harshness of the process, tag durability, process and tagging speed determines tracking intensity. A complete production line may contain processes such as casting, extrusion, sawing, turning, transfer, storage, heating, forging, blasting and heat treatment. Process information can be stored in the factory-cloud and can be associated to a specific workpiece by means of a master-identity. It is not necessary to store the complete master-identity on a tag fixed to the workpiece. Local or temporary identities can be assigned and reused at the machine level provided that the corresponding master-identities are distinct. In case economic and physical conditions desire for the next process relabelling can be performed. Tracking of a workpiece over a master-identity using various local-identities throughout the production line requires networking of the technical tracking systems in real time. Manual identification, transfer and registration of identities can be a part of this network. With such manual networking practise the tracking problem reduces to localized tracking of workpieces throughout individual processes.

2.1. Process formalisation

Process in a forging production line may be clustered into the following process categories (PC):

- (PC1) Tag endures throughout the process.
- Tag does not endure throughout the process and
    - (PC2) workpieces are processed in sequence
    - (PC3) batch processing is performed.

Processes belonging to PC1 do not damage the tag applied onto the workpiece, so the tag can be identified flawlessly after processing. Examples are storage, transfer or heat treatment. Workpieces qualified as scrap can be identified and registered easily. *Processes belonging to PC2* do damage the tag, but the sequential processing allows the tracking of the identity within and after processing according to the identity scanned before the process. Parts can be qualified as scrap during or right after the process. Especially scrap determined and separated during process has to be registered in real time, which can be automated or performed by manual triggering. State-of-the-art applications such as force measurements and part proximity sensors located at grippers can be used for recognition of missing parts. *Processes belonging to PC3* damage the tag, the individual identity of produced part is lost since many workpieces are processed together. In this case individual relabelling is not practical due to high production rate or constraints given by logistics. Such processes (e.g., heat-treatment, blast cleaning) consequently permit only batches to be tracked. Individual information of workpieces processed together can be merged in a "statistical representation" stored in the factory-cloud and only can be associated to batches.

Tagging time being longer than the process time in case of PC2 hinders the tracking of all the workpieces individually unless multiple tagging stations are employed. Valuable linked information on processes and workpieces however can be created for some of the workpieces with a single tagging station.

Batch tracking can be enriched by inline measurements to improve on-site the information content of the tracking. Henceforth tracking with additional individual information can be performed during the rest of the process chain. For example, the workpiece size, usually having a high scatter frequency, is an important issue for process control and for posterior big-data analysis on parameter dependency. On-site measurements can be extended with fast geometry measurements (such as shear face of a billet) or with eddy-current measurements, if applicable.

The operative tracking actions are tagging with the (part or batch) identity and tag scanning to recall the (part or batch) identity and the corresponding information in the factory-cloud. The computational tracking actions are locating the identity in the factory network, providing the required information from the factory-cloud to the process machine and storing the generated production information to the factory-cloud. Locating the identity in the factory network is either achieved by onsite tag scanning or "virtually" without the aid of a physical tag on the workpiece and can be named as a *virtual tag*. If a strict transfer protocol with sequential processing is implemented for a range of processes, a virtual location tracking can be performed using onsite busy/free location switches. These location switches can be realised either by part sensors or digital monitoring with image processing. In the absence of a strict transfer protocol, location switches have to be supported by motion tracking to perform the virtual tracking. Motion tracking could be implemented with a network of video cameras and image processing techniques. Camera locations and motion paths have to be planned to yield a robust configuration.

The category of a process can be altered by a process redesign to improve the traceability. Workpiece conveyors or workpiece carriers with a strict preservation of processing order instead of a disorderly transfer are trivial examples for such an improvement. At least, small workpiece containers providing reduced batch sizes can be used to increase the specificity of the statistical representation of the associated information.

2.2. PLC-based data acquisition and processing

The individual interfaces of the connector software do run on control devices and the standardized interface runs in the factory-cloud. The individual interface is basically implemented as state machine that can be integrated into the PLC code. Two major cycles can be distinguished. Firstly, a "read"-cycle that scans the protocol structure and extracts data depending on the bus system. Secondly, a "write"-cycle that uses a REST model to describe the extracted data. The measured process parameters are converted and mapped onto the model and posted to the standardized interface that runs on the cloud server. The standardized interface forwards the data for further processing. It is either stored in a relational database where data analytics techniques can be applied or forwarded to a real-time database to conduct ad-hoc calculations and online analytical processing (OLAP). The real-time database is used for the association of workpiece identity and process parameters along the entire process chain. It allows an online tracking of single parts or batches. The general concept is depicted in Figure 1.

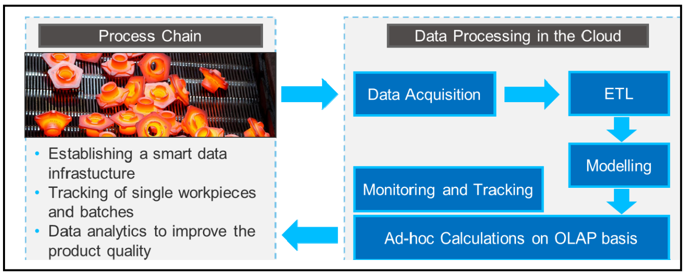

Figure 1. Concept and system architecture.

2.3. Multidimensional modelling and data driven traceability

To achieve an efficient monitoring and tracking, an OLAP model has to be created under consideration of the data spaces of the single process steps. The model is separated into dimensions of time, space and product information, Figure 2. The dimensions contain an internal, hierarchical structure where each branching is described by an element. Basic elements are associated with data vectors and mark the innermost layer of the data model (product type P with id x). Higher layers (batch A of product type P) cumulate the information of lower layers by applying aggregation procedures. Thus, heterogeneous data can be integrated into one homogeneous model due to the fact that it is possible to associate different layers with different granularities. This factor enables the tracking of a flexible amount of parts by navigating through layers. The modelling approach is visualized as cube in Figure 2. According to Shin et al. [14], three major properties are required for n-dimensional model structures: 'commonality', 'reusability' and 'composability'. Subsequently, authors intend to widen the 'composability'-aspect by a meta-modelling approach to define thresholds and rules for process parameters to enable an effective limit monitoring. Regarding the described process chain, varying environmental conditions indeed do affect the quality of process and product. For example, decreasing quality of coolants depends on numerous factors including useful life (time dim.) and machine (space dim.). Consequently, these side effects can be formalized and mapped on the dimension structure and projected onto the meta-cube. Hence, an automated monitoring on the basis of expert knowledge can be realized.

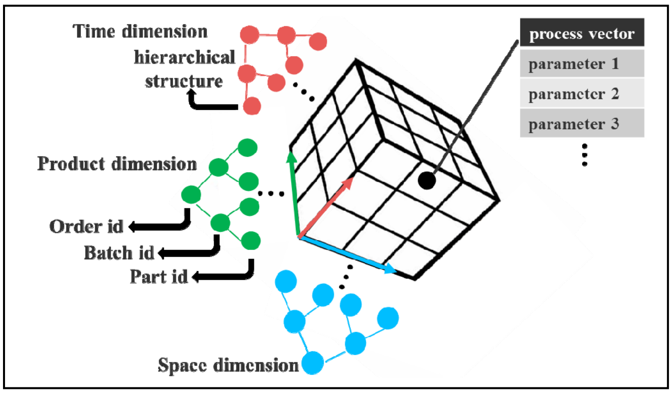

Figure 2. Multidimensional model of process and workpiece information.

3. Practical tags and tagging experiments

The design of a complete tracking system considers applied processes, part geometry and material. The discussion here is limited to the comparison of the known tag characteristics and the investigations on the not yet tested characteristics. In this context, laser-engraving tests on hot steel and aluminium are conducted and the results are compared with needling. Part or batch tracking solutions for operations such as machining, sawing, transfer or storage are already in industrial praxis. The harsh forging environment, possibly covering heating, forging, blasting and heat treatment allow RFID, labelling, needling, marking, laser-engraving and virtual tagging to be useful throughout these processes. Tags should not cause any harm, they must endure and could be tagged around 500°C for aluminium and 1200°C for steel. Oxide-layer has to be removed before tagging and hindered afterwards but the tag should endure the development of the oxide-layer. A heatproof RFID is durable up to 350 °C at the transponder, [15], with a size of 10×7×3 cm being practical on containers for batch tracking. There are also labels durable up to 1250°C, providing flexible size and content for individual or batch tracking [16]. The difficulty arises while attaching, keeping and removing the labels. Although they are just superficial, needling, marking and laser-engraving become a part of the workpiece. They affect the geometry and even the material locally. Table 1 compares functionality of needling, marking, laser-engraving based on market research conducted during experiments.

QR-Code can provide successful recognition even a part of the label is damaged. Figure 3 demonstrates on the left a QR-Code generated by a fibre-laser on aluminium at 550°C and damaged afterwards by collisions with other parts during shaky batch transfer in a container, yet the recognition is functional. Figure 3 demonstrates on the right cold marked steel which is covered by oxide-layer for three hours at 900°C. Visible markings on the oxide-layer and on the clean surface after removal of the oxide-layer are both identified by QR-Code readers. If the QR-Code reader should fail, the attached clear text is thoroughly legible.

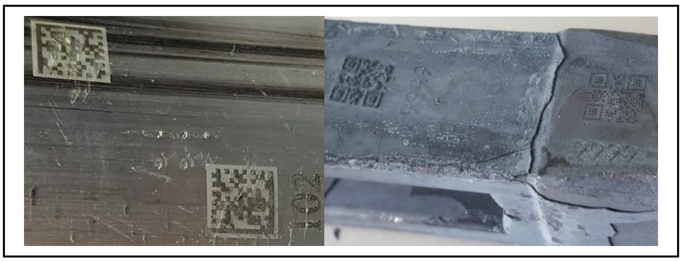

Figure 3. QR-Codes generated by fibre-laser: Aluminium at 550°C damaged by collisions (left); Steel at RT covered by an oxide-layer development at 900°C for three hours (right). All codes are recognised successfully.

Table 1
Comparison of functionality of commercial tags

	Marking	Needling	Fiber Laser-Engraving (50W)
Content	Clear text	QR-Code, Clear text	
Marking depth	Limited	Strike energy	Beam energy and repetitive shots
Tagging Time	~ 1 sec.	~ 4 sec.	~ 8 sec. for 50 W Fiber Laser (increases with size and surface preparation, reduces with power)
Clarity	Missing contrast	Missing contrast	Superior due to surface preparation
Size	Marker size	Needle size	Flexible
Resolution	-	Fixed	Flexible within a label
Surface Curvature	Slight curvatures		Flexible with adaptive focusing
Clear Text	High quality	Dotted	Dotted with flexible resolution
Temperat.	Tested at 550 °C for Aluminium, 1200 °C for Steel		
Investment	~ 10.000 €		~ 30.000 €
Scanning automation	Optical recognition	QR-Code reader,OCR	QR-Code Reader, OCR (Superior if surface preparation is performed)
Blasting resistance	Poor. Increase with the dot size and depth.		

Needling and laser-engraving can both be used to mark QR-Codes and clear texts on the surface. Since the resolution of the needling is limited with the needle diameter the marking size is not flexible. The depth of dots can be influenced by the impact energy. Overlapping dots by needling is not practical but this is totally harmless for a laser-engraver and can be performed to increase the depth of each dot and even the resolution of the engraving. A QR-Code together with the content in clear text is difficult to generate by needling compared to laser-engraving. Figure 4 compares a high resolution laser-engraving (where a single dot is generated with many tiny dots) with the result of the needling to demonstrate clearly the limits of the needling and the capabilities of laser-engraving. A laser-engraving with single-dot-resolution is also provided to demonstrate the difference between the dot characteristics. The larger and deeper dot characteristics provides a better durability against blast-cleaning.

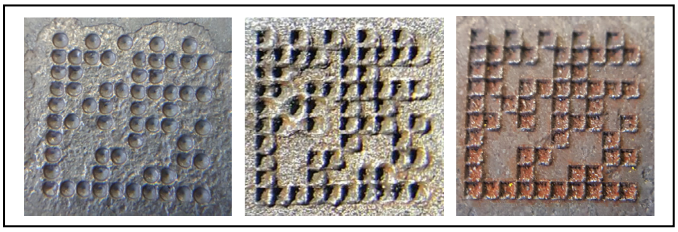

Figure 4. QR-Codes generated by needling (left), low resolution laser-engraving (middle) and high resolution laser engraving (right), all with successful optical recognition.

4. Experimental assistance system for single/batch tracking

In order to test the system architecture, a simulative process chain is used. The PLCs of the environment run with a cycle time of 1 ms which prevents the loss of relevant process information due to low sampling rates. The data space includes 18 different sensor values (real and simulated) of 5 consecutive process steps. The standardized interface runs in the cloud and forwards the data in JSON format to the OLAP database. The transmission of the data can be controlled in various ways. Firstly, a constantly frequented query can be executed by the REST server in the cloud. Alternatively, an event-driven data transfer can be realized through the customized interfaces.

In case of different amounts of parts being tracked, the ETL stack maps the new information on the hierarchical dimension structures. This projection causes the creation of higher layers for batch tracking. As a result, new elements are generated within the hierarchy. Therefore, different process data structures of varying products and amounts can be adapted. The same flexibility applies to any other element of any other layer in the hierarchical dimension structure. Hence, it is possible to track different amounts of parts by navigating in the hierarchical dimension structure. Batches can be associated with the corresponding process data and cumulated values of the measured data. In contrast to single workpieces, the tracking of multiple parts demands the safe estimation whether all parts fulfil the quality requirements. The navigation to the batch layer automatically monitors all relevant parameters characterizing the batch and gives the user an overview on average values. These values are calculated based on all parts of the batch. The whole data integration process is cyclically executed with parallel computing enabling online monitoring and tracking. It is implemented as web interface for a flexible access from a variety of devices. The first view allows the limit monitoring of process parameters so the exceedance of limit values is lighted. The user navigates in all three major dimensions of time, space and product. Thus, he can select single workpieces or batches at a certain process step at a point in time of choice and the according process data will be displayed. In the second view trajectories and deviations are observable providing an efficient control of process parameters.

4. Conclusion

Authors propose a general workpiece tracking methodology for hot forging plants covering process formalisation, multidimensional modelling of data-driven-traceability and PLC-based data acquisition and processing. Practical tags are reviewed and tagging experiments are performed to extend the possibilities of individual workpiece tracking. The realisation of individual workpiece tracking for high production rates requires re-design of processes like transfer, storage heating and heat treatment based on the introduced process formalisation. Real-time registration of scraps is a requirement in the tracking problem. QR-Code with clear text extension is suggested for manually aided automation. QR-Code standards are based on the unit square dot fully covering the grid-cell. Needling and laser-engraving in the single-dot-resolution however generate round dots without filling the corresponding grid-cell. Furthermore, the colour and contrast in a dotted grid-cell is not optimal. Readability of a QR-Code depends on the recognition of a dot, having a distinguished contrast from a free grid-cell. Since DIC based identification use this standard technique which is biased towards the printed codes with sharp contrast difference, identification of the engraved codes may fail in case of bad lighting. In this study, standard systems are used and mostly successful results are obtained with proper lighting. However, the need of improved software for DIC based identification is also felt.

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References

[1] Bauernhansl, T., Krüger, J., Reinhart, G., Schuh, G., 2016, WGP-Standpunkt Industrie 4.0., Wissenschaftliche Gesellschaft für Produktionstechnik WGP e.V.
[2] Liewald, M, Karadogan, C., Felde, A., Lodwig, R., 2017, Development and Integration of Digital Technologies in the Forging Process Sequence, New Developments in Forging Technology, 245-256.
[3] Connolly, C., 2005, Part-tracking labelling and machine vision, Assembly Automation, 25/3:182-187.
[4] Song, L., Mohammed, T., Stayshich, D., Eldin, N., 2015, A Cost Effective Material Tracking and Locating Solution for Material Laydown Yard, Procedia Engineering, 123:538-545.
[5] Dai, J.B., Fan L., Lee, N.K.S, Li, J., 2017, Joint optimisation of tracking capability and price in a supply chain with endogenous pricing, IJPR, 55/18:5465–5484.
[6] Denkena, B., Grove, T., Seibel, A., 2016, Direct Part Marking by Vibration Assisted Face Milling, Procedia Technology, 26:185-191.
[7] Vedel-Smith, N.K., Lenau T.A., 2012, Casting traceability with direct part marking using reconfigurable pin-type tooling based on paraffin–graphite actuators, Journal of Manufacturing Systems, 31:113-120.
[8] Montanini, R., Quattrocchi, A., Piccolo, S.A., 2016, Active thermography and post-processing image enhancement for recovering of abraded and paint-covered alphanumeric identification marks, Infrared Phys Technol., 78:24-30.
[9] Stolkin, R., Greig, A., Hodgetts, M., Gilby, J., 2008, An EM/E-MRF algorithm for adaptive model based tracking in extremely poor visibility, Image Vision Comput., 26/4:480-495.
[10] Akin, O., Erdem, E., Erdem, A., Mikolajczyk, K., 2016, Deformable part-based tracking by coupled global and local correlation filters, J. Vis. Commun. Image R., 38:763-774.
[11] Kanagamalliga, S., Vasuki, S., 2018, Contour-based object tracking in video scenes through optical flow and gabor features, Optic, 157:787-797.
[12] He, T., Mao, H., Yi, Z., 2017, Moving object recognition using multi-view three-dimensional convolutional neural networks, Neural Comput & Applic, 28:3827-3835.
[13] Faul, A., Jazdi, N. and Weyrich M., 2016, Approach to interconnect existing industrial automation systems with the industrial internet. 21st IEEE International Conference on Emerging Technologies and Factory Automation (ETFA) 2016.
[14] Shin, S.J., Woo, J. and Rachuri, S., 2014, Predictive analysis model for power consumption in manufacturing, Procedia CIRP 15:153-158.
[15] http://sawcomponents.de/produkte/saw-sensorik-und-rfid/
[16] http://heatproof.eu/products/