21ST INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED17
21-25 AUGUST 2017, THE UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER, CANADA

TECHNICAL INHERITANCE: INFORMATION BASIS FOR THE IDENTIFICATION AND DEVELOPMENT OF PRODUCT GENERATIONS

Mozgova, Iryna (1); Barton, Sebastian (2); Demminger, Christian (2); Miebach, Timo (3); Taptimthong, Piriya (4); Lachmayer, Roland (1); Nyhuis, Peter (3); Reimche, Wilfried (2); Wurz, Marc Christopher (4)
1: Leibniz Universität Hannover, Institute of Product Development, Germany; 2: Leibniz Universität Hannover, Institute of Materials Science, Germany; 3: Leibniz Universität Hannover, Institute of Production Systems and Logistics, Germany; 4: Leibniz Universität Hannover, Institute of Micro Production Technology, Germany

Abstract

Industry 4.0 opens great potentials in development and production processes by networking of machines and systems as well as all processes along the lifecycle components. E. g., new developed intelligent systems are able to collect, store and transmit data during their complete lifecycle based on physical principles. For the development and usage of such systems, the basic processes are analyzed, information chains are set up and targeted information from the life cycle is identified, transferred and returned to the product development phase. This aims to adapt the products and to develop new product generations. This previously presented approach has been named Technical Inheritance. An important aspect here is the relevant key information on the basis of which an identification and analysis of the state for each exemplar of the product is made. In order to implement such identification in the context of Technical Inheritance a so-called genetic code of the product is used. This aspect of the methodology of the Technical Inheritance will be discussed in detail.

Keywords: Design methodology, Design process, Product Lifecycle Management (PLM), Technical Inheritance, Smart product

Contact:
Dr. Iryna Mozgova
Leibniz Universität Hannover
Institut für Produktentwicklung und Gerätebau
Germany
mozgova@ipeg.uni-hannover.de

Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 6: Design Information and Knowledge, Vancouver, Canada, 21.-25.08.2017.

1 INTRODUCTION

To fully gain the advantages of Industry 4.0 smart components are required; manufacturing in the framework of this concept involves the exchange of data between all parties engaged in the production chain. The solution corresponding to Industry 4.0 is a single process in which the production equipment and the products are integrated as active system components to control their production and usage processes. In such context, Industry 4.0 can be interpreted as a synergy between smart parts and intelligent manufacturing. Key feature and challenge of the new industrial production is a communication between sensors, actuators and assembly units. Smart components can be seen as abstract objects with the following properties: having a standard interface for data exchange; can transmit and store information about their condition and location; may analyze their current state; are described by models; imply sufficient autonomy and flexibility. Instances of these abstract objects are uniquely identifiable products that provide access to information about their condition throughout the life cycle.
Within the scope of the Collaborative Research Center CRC 653, “gentelligent” smart products (or components) are developed which are equipped with "genetic" and intelligent properties (Denkena, 2014) and characterized by featuring a feedback of inherent stored information to the processes of product and production evolution. Therefore, the gentelligent products require sensory capabilities to detect and measure e.g. mechanical loadings or temperatures. Such gained information acquired during the production cycle and the life cycle is applied to efficiently improve both the product and the production processes. Using the feedback of information gained and verified during the life cycle in engineering departments and productions shops, an adaptation process is realized.
Hence, we are talking about systems that are configured or adapted to new tasks. These serve themselves, analyze themselves and change processes, depending on the requirements. The effective development of such systems requires a new engineering approach. This article presents the within the scope of CRC developed approach to the design, manufacture and operate intelligent products, known as Technical Inheritance (TI).

2 THE CONCEPT OF TECHNICAL INHERITANCE

There is a large number of studies showing that technical systems in their development are subject to complex statistically significant trends, describing logical consistent transitions of systems from one particular state to another. A partial review of these studies is given in (Lachmayer, Mozgova, Reimche et al., 2014). The laws of development of technical systems are statistical in nature, i.e., these are not required to be fulfilled. They are an external manifestation of some kind of natural selection in the world of technology. Therefore, the system which complies most of the relevant requirements of the environment and society is chosen.

2.1 Industry 4.0: information feedback

The level of economic and socio-political development of society depends on its scientific and technical progress. In due time Joseph Schumpeter (Schumpeter, 2006) offered the model of circular flow in economic development. The start of a new cycle is marked by a certain industrial revolution and indicates the emergence of fundamentally new production and economic environments in a society. Starting the industrial cycle is characterized not only by the emergence of new industries and economic spheres, but also fundamental changes in existing industries. The idea that the business result can be either the finished product or service is changing today. Practically any product bought by the consumer purchases also a set of certain services. To the contrary, together with acquisition of services also certain products are purchased. Today widely observed are both, individualization and standardization as well as unification and packaging services. Services are more and more becoming similar to the products (Gembarski and Lachmayer, 2017). Having information about the clients and their manner of using products allows to receive the information about the current state, necessary preventive measures, violations in the operation mode. Using this information, it is possible to offer the user to purchase a new product or to upgrade an existing product at the right time and in the right form. So, we are talking about a meaningful exchange of information between buyer and seller or between developer and user. This exchange involves the systematic collection, storage and processing of data during manufacturing and usage of products. That is a complete information support of the product throughout its life cycle. Mechanisms and methods of data collection and analysis should be provided at the stage of product development. In this case, since we are talking about the development of the current product generation on the basis of the information collected on the manufacturing and usage of previous generations, the analysis of the laws of development of technical systems does not lose its relevance in the context of the ongoing currently fourth industrial revolution.

2.2 Technical Inheritance

Within the concept of Industry 4.0, various sensors, equipment, products in manufacturing and operation, as well as related information systems are combined within a chain that goes beyond a single enterprise and single user. These interrelated cyber-physical systems interact with each other on the base of standard and special protocols, and are able to independently collect and analyze data to predict failures, customize and adapt to environmental changes.

TI is defined as a transfer of assembled and verified information from manufacturing and application to the next product generation (Lachmayer, 2014). The goal of TI is the development of a new generation of the product adapted to the new or changed requirements on the basis of information on development, manufacturing and usage of the existing generations of a product. Here, one of the central questions of the evolution of technical products is how to consider inheritance and how to transfer information from one generation to the next. In this context, an important role is played by two aspects. The first aspect is the ability of a component to collect data by using special materials with sensory properties. The main phase of the product life cycle, as well as methods for identifying relevant information and methods for analyzing the data collected are considered in (Lachmayer, Mozgova, Sauthoff, Gottwald, 2014). Information accumulated during the manufacturing and usage is applied in the development of a new generation. This takes into account the identified data collected through the operating features in different conditions. To obtain representative data it is necessary to analyze the data during manufacturing and usage not only for a single component, but for the component population. Within the scope of Paradigm of TI (Lachmayer, 2015) the population consists of all generations of individuals of a technical system, product and process as well as a model at the current time. The generation is a group of individuals with the same level of development. The individual is the smallest considered technical system, product, process or model in a population. The second important aspect for the evolution of components is an ability to identify each component and the possibility to restore the full picture of the life cycle at any time, including the stages of development, manufacturing and usage. Here, the TI introduces the concept of the Genetic Code (GC) of the component. As genetic information of a component can be constituted the basic information which is necessary to identify or reproduce components or which helps to interpret geometric descriptions or information about materials. This information can be stored as static, unchangeable data in the component.

3 EVOLUTION OF GENTELLIGENT COMPONENTS

The within the CRC developed materials, technologies and processes, the gentelligent components feature abilities to load, store and to process information such as applied forces and temperatures during their production and usage. Thus, the gentelligent components are characterized by inherent sensory properties and the ability to store data inherently and to communicate between themselves. One example would be a wheel carrier, which acquires loading data during the car movement to improve and optimize the geometry of new generations of components.

3.1 Typical life cycle of a smart component

TI was realized by design evolution of a gentelligent components based on collected data to adapt and optimize the next component generation. Data is obtained during the component's manufacturing as well as during usage and can be applied to efficiently improve the process requirements concerning product development as well as manufacturing and maintenance. Miscellaneous data is available in all phases of the product life cycle which can be processed to gain valuable information for the development of following generations of gentelligent components. Data can be stored by means of a specially developed GIML format (Denkena, 2016). By means of a further development of specification and modelling techniques, the life cycle of manifold technical systems can be modelled accurately regarding the information flow. Furthermore, a subsequent analysis allows to identify development relevant information.

3.2 Evolutionary adaptation of a component

Through the processes of TI, information should be produced in a product-specific manner, which in this way creates a great advantage for the development of the new generation of a component. Evolutionary adaptation of the technical system includes an inverse information relationship, providing a suitable response of complex self-controlled systems to changing environmental conditions. Evolutionary adaptation is a process of transferring specific information for this population of products or components. The information is stored in the respective database. Each new generation of components, passing in its life cycle through phases of development, manufacturing and usage, generates own information (Figure 1). Rational use of accumulated information about production and usage of the previous generations of a product allows to accelerate the process of development of new generation. Or it allows to take into account important aspects of production and operation not considered before, and to adapt the product quickly. Microevolution processes are observed in the process of evolutionary adaptation. Since in the context of the TI intelligent products with sensory properties are present, the development process itself is iterative and includes the phases of development and optimization of component geometry, the selection of a suitable material and choice of sensors. The sensors can be inherent, in case of manufacturing of components from materials with sensory properties, as well as external.

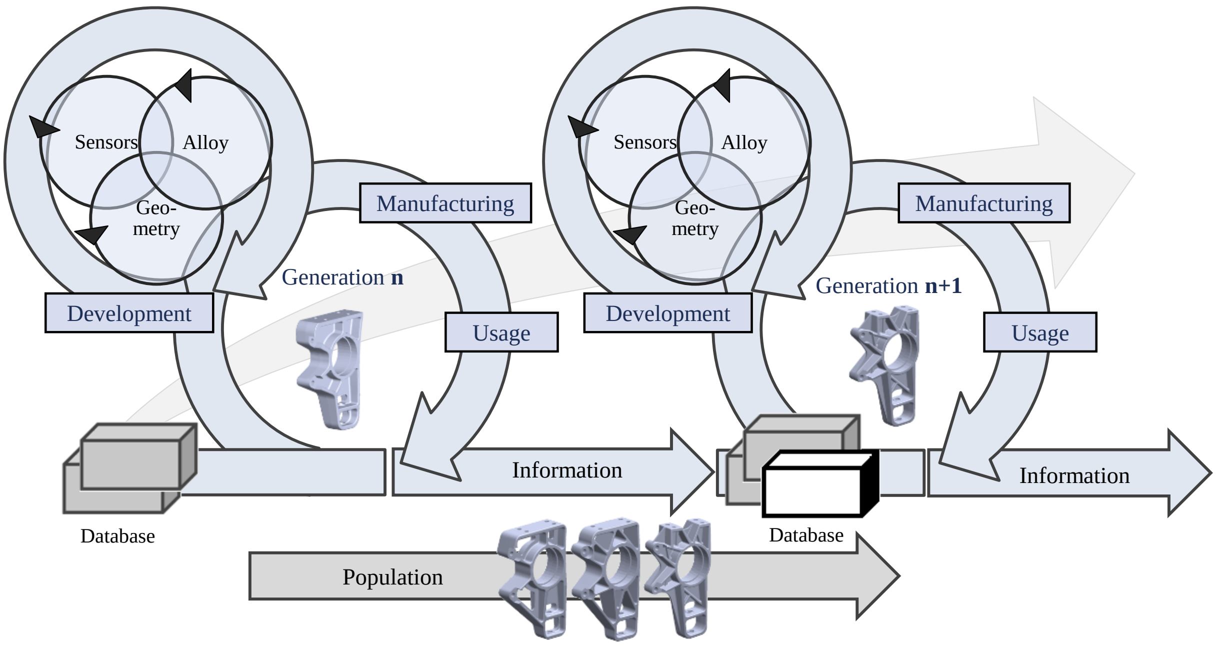

Figure 1. Evolutionary Adaptation of a Component

Each development phase has an iterative character. Thus, during developing and optimization of the geometry of the component, properties of alloy are considered. The selection of type of sensor, in turn, depends on alloy and geometry of a component. Depending on the expected loads and simulation results obtained during the geometry development, it might be necessary to change e.g. the properties of the alloy from which the component is made of. That would entail the following changes in the selection of sensors. Positions of sensors, for example, on the component surfaces, also have to be planned not only taking into account critical or characteristic places of loading, but also taking into account the availability of locations for reading and writing data, and also for preventive maintenance, repair or replacement. That can demand, in turn, a change of the geometry of the component.

4 TECHNOLOGIES FOR INTELLIGENT DATA READING/WRITING

Here, the research focuses on investigating and adapting methods, tools, utilities and processes to support a comprehensive product development. This includes efficient process runs to realize a high degree of automation as well as an integration of knowledge and to increase the flexibility within product chains. One of the main challenges in linking and reutilization of information is defining an appropriate and flexible data format, since both - during a life cycle as well as in subsequent product generations - additional types of information have to be included into the data format.

4.1 Standardization of Data Exchange and Genetic Code of a Component

For a standardization of data exchange the XML-based hierarchical Gentelligent Markup Language (GIML) had been developed; it is feature-based and regards a life cycle oriented hierarchy (Denkena, 2016). Regarding an attribute based hierarchization the GIML format contains certain levels namely product, component, design element, feature, product and usage levels. To support comprehensive life cycle product models an approach based on a generative parametric modelling (Sauthoff, 2014) was development. One of the use cases so far investigated by a description of the geometry of a component for a production process regarding features such as bores etc. (Denkena, 2016) is a dynamic work plan compilation. In addition to a standardization of the storage and data exchange format for effective condition monitoring and control in the context of a paradigm of TI, an effective method of quick and full identification of the main characterizing information of the component for all lifecycle is necessary. As such information, the GC was allocated. The GC of a component includes several parts and levels of parametrization (Demminger, Mozgova et al., 2016). The GC can be stored, for example, on the surface of the component, and can be written, read or modified at any time of the component lifecycle. Over the entire product life cycle collected data, for example, the load undergone by the components during the operation can be stored in GIML-format.

4.2 Gentelligent materials

Within the CRC several gentelligent materials, technologies and processes have been developed as described. Magnetic magnesium alloys have inherent ferromagnetic properties, which enable two major abilities. These enabling technologies are based on magnetism, or, more briefly, ferromagnetism. Commercial available magnesium alloys like AZ31 or AZ91, which are mainly used for lightweight applications in the aircraft and automotive industry, have paramagnetic properties (Friedrich and Mordike, 2006). Therefore, such alloys are not usable for magnetic data storage or sensory applications using magnetic properties. The data storage is performed using a magnetic write/read head. Hence, information like ID, production date, material composition are storable inherent with the component (Demminger, Mozgova et al., 2016). To detect mechanical loads, introduced to a component made from magnetic magnesium alloys, the harmonic analysis of eddy current signals is used (Feiste, 2003). The basic physical phenomenon is the inverse magnetostrictive effect, which describes the relation of deformation of a ferromagnetic material and the change of the ferromagnetic strain according to the applied mechanical load (Cullity and Graham, 2009).

In context of TI, the overall development of magnetic magnesium alloys is divisible in three sections, as shown in Figure 2. In the beginning, one idea of the CRC was a new lightweight material with inherent sensory properties. Magnesium has a great lightweight potential, but, as described, not the intended properties. For this reason, the first generation of the magnetic magnesium alloys have been manufactured from common magnesium alloys, which were manipulated with commercially available magnets. More precisely, a milling head was manufactured in a high-pressure die-casting process from aluminium-based magnesium alloy AZ91 with an integrated permanent magnet. The magnets have been applied to the steel mold during the mold preparation process as an insert component. After preparation, the magnet was integrated into the milling head during casting process. As a result, data is magnetically storable inherently on each component. The second generation of magnetic magnesium alloys have been equipped with inherent magnetic properties by adding fine ferromagnetic powder to the magnesium melt, instead of insert components. The used magnetic powders are commercially available, like NdFeB, AlNiCo and SmCo, and have been added in several mass fractions to the magnesium alloy AZ91. By this measure, the whole component got inherent magnetic properties. As a result, on each area of the component’s surface the magnetic data storage of information can be performed. Additionally, the load detection using the harmonic analysis of eddy current signals is enabled. Within the context of TI, the magnetic properties have been selected and been inherited to the next generation of the alloys. Based on the determined results, the latest generation of magnetic magnesium alloys was developed based on pure alloy elements to be independent of commercial alloys and commercial magnetic materials (Klose, 2013). Furthermore, a major advantage is to adapt the alloy's specifications to the special requirements regarding to mechanical and magnetic properties, as well as processability, more precise castability.

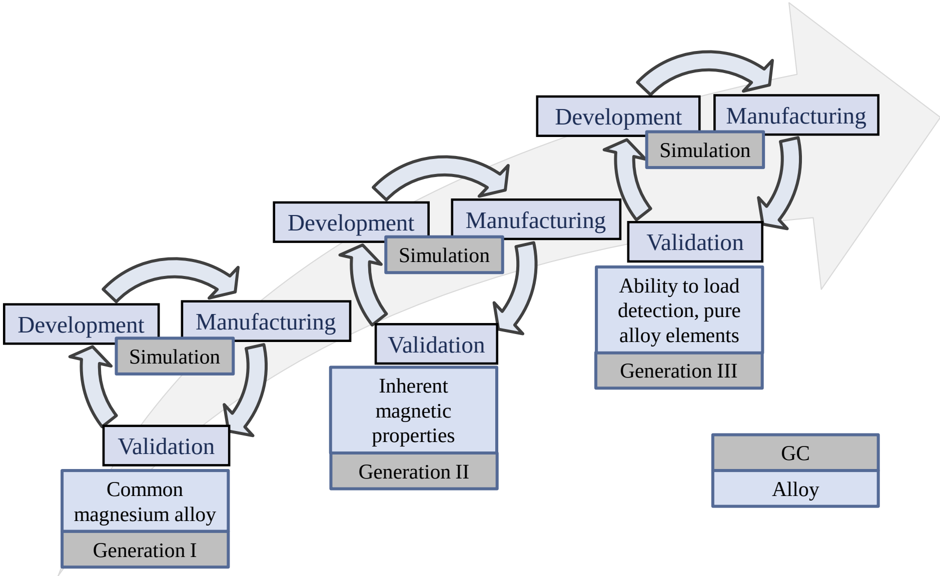

Figure 2. Evolution in development of Magnetic Magnesium Alloys

Since, the desired magnetic magnesium alloy has been characterized in laboratory scale, the next step is the production of usable components. In this context, it is important to consider the requirements of all involved participants. For example, the casting geometry has to be arranged with the construction department to meet both, the constructive requirements and the requirements of the casting process. In addition to this, the used eddy current sensors also have requirements, like contact surface or the environmental conditions. So, there is an evolution in developing magnetic magnesium alloys and afterwards in processing as well.

4.3 Adapted load sensors

Looking at data acquisition throughout the use of a product, the employment of integrated sensors is essential. They create the possibility of a continuous record of strains and loadings a component is exposed to. Taking advantage of already known component data such as alloy, geometry and relevant measuring points which are stored within the GC, the choice of a suitable sensor can be carried out by taking these information into account plus information out of a sensors database (Figure 3).

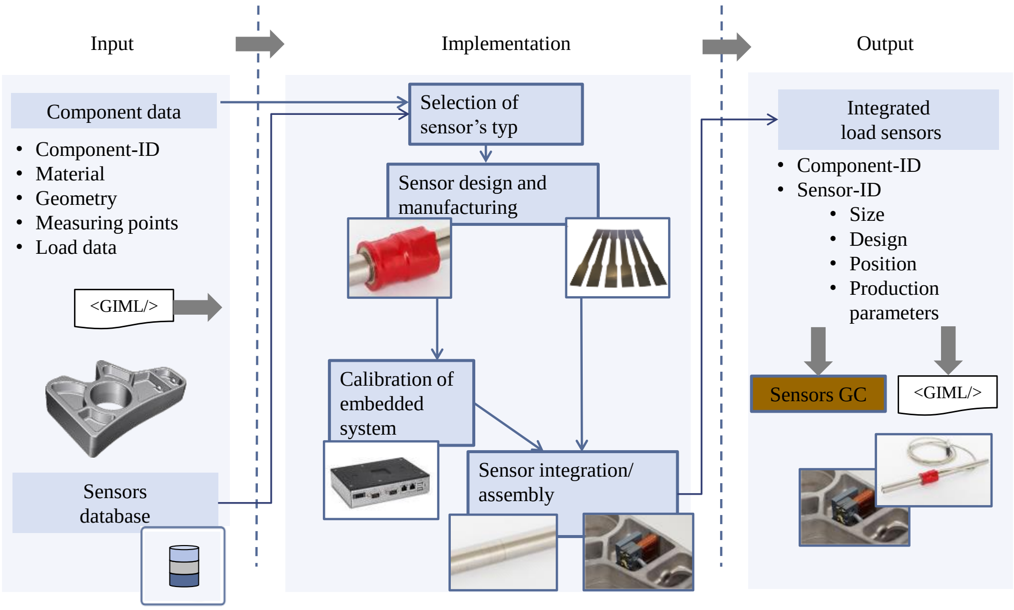

Figure 3. Implementation of Sensors in a Component

Depending on the already named parameters also the application of a product and the type of desired information are taken into consideration for the choice of a suitable sensor. In the scope of the CRC there were different new types of sensor technologies developed. For example, these are harmonic analysis of eddy currents for strain detection and so called yield-stress sensors. The harmonic analysis of eddy current's is used for determining strain using the villary effect. This sensor technology facilitates a live monitoring of loadings (Klose, Demminger et al., 2013).
The development of the yield-stress sensor's design ended up in a sensor type which significantly surpasses the level of known monitoring technologies. These sensors create a unique possibility to measure if a set yield strength level was exceeded during utilization of a component. This technology is based on globally strain-hardened metastable austenitic materials and a local heat treatment of the formed martensite in the surface area. Further, the sensor doesn't need any electronics while the usage of the component and the load data can be read out at any time, for example during maintenance. After choosing one sensor technology a calibration and the fitting of the sensor to the given geometry of the component have to be taken. Regarding the yield-stress sensor technology care must be taken in the orientation, the positioning and the adjusted yield strength of the sensors, depending on the application (Barton et al., 2016), (Mróz, 2013).
Coming back to the process of identification, several data sets are then stored as sensor ID. Except the identification code important information are the sensor type, size, shape, position and manufacturing parameter. The measured data throughout utilization are an excellent base for a condition based maintenance and for developing the next generation of the given components.

4.4 Example of Genetic Code

The main parts of GC are depicted in Figure 4. In addition to the Alloy GC and design elements the code includes the parameterized skeleton that provides the location of the connecting surfaces. Skeleton structure remains unchanged. Part of the set of the parameters of each design element is the set relating to connecting areas which at the neighboring design elements is identical. Thus, the Design GC of the component includes skeleton parameters and parameters of the design elements.

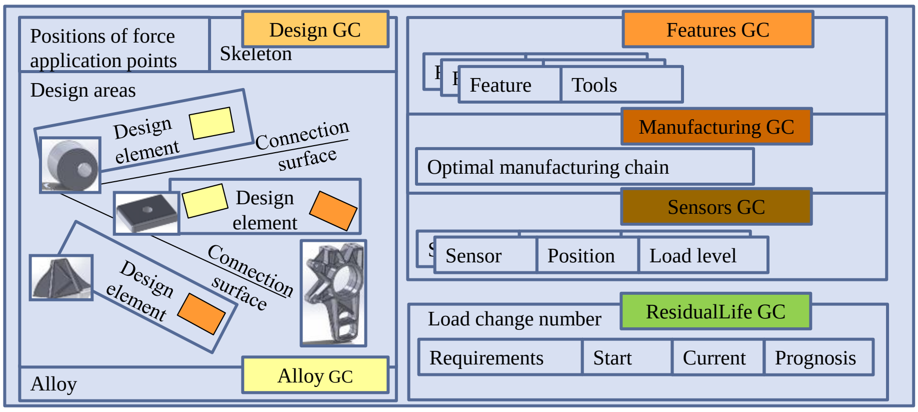

Figure 4. Example of Genetic Code of a Component

Features GC is composed of parts, including the feature codes processed that are part of the components and tools. Codes of features and tools are stored in the respective databases. Length of Features GC, as the length of Design GC, and Sensor GC are not fixed. The size of Residual Life GC is fixed; the code includes information about the required load change number during the component life cycle, the load change number after the manufacturing process, current load change number in the usage phase and the estimated number of load changes as the result of the condition-based maintenance algorithm.

4.5 Storage of Genetic Code

Through a life cycle of a gentelligent component, information related to each gentelligent component is generated and stored in a central databank as depicted in Figure 5. From development to production, the flow and content of information is determined and thus a batch of components possesses defined GC which are static information. During usage, however, components are employed differently and have their own individual experience, such as loading and maintenance.

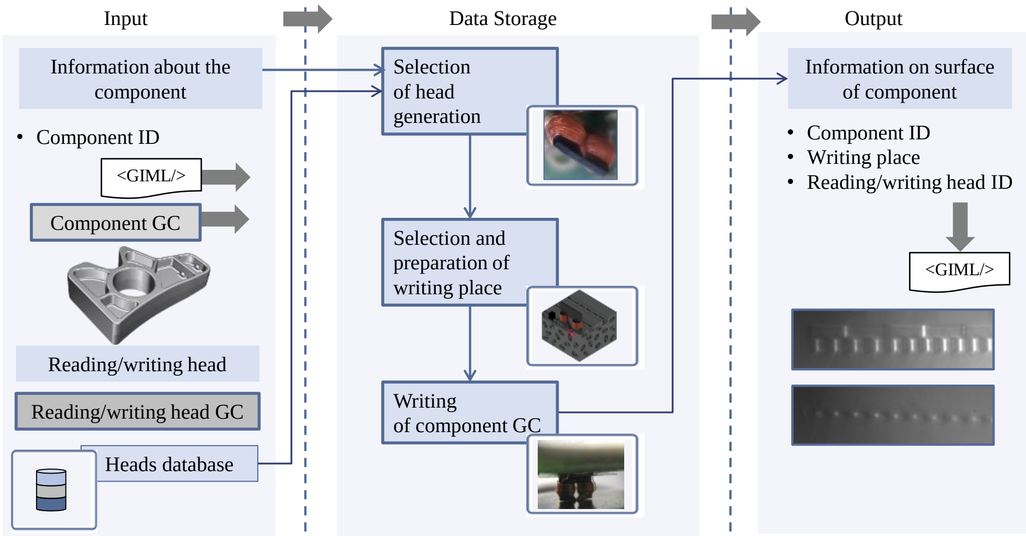

Figure 5. Data Storage

Except a component ID, usage information like the last activity and maintenance date and remaining service life are dynamic. Most of the time, the usage information can be stored centrally, if users or maintenance persons have access to the central databank. In the context of gentelligent components and TI, this implies a tight network interconnection between manufacturers and users. If such interconnection is not possible, for example, a component serviced in a small shop, inherent storage comes in to complete the information flow. One of inherent storage technologies developed in CRC is inherent magnetic storage within component surfaces. Unlike conventional static storage techniques being labelling and engraving, the inherent magnetic storage is dynamic allowing stored information to be overwritten without necessity to change a medium. Furthermore, the intrinsic aspect of this technology means that the component itself is the medium. Loss and mistake of information due to separation and falls are automatically prevented. The inherent magnetic storage is based on the principle of hard disk drive and consists of a read head, a write head and a medium (Gatzen, 2006). Magnetic properties and surface regions where information can be written are defined in a component GC. A reading/writing head GC contains, for example, head geometries, construction materials and a type of head core. These GCs are sent to a reading/writing system for evaluation and selection of a suitable reading/writing head, control parameters of a write process and a surface region for recording.
A magnetic sensor on a reading/writing head retrieves stored information back by detecting magnetic transitions between data bits (Belski, 2012). An example of data tracks written using different types of reading/writing heads (Taptimthong, 2016) is shown in Figure 5.

4.6 Technical Inheritance: Evolution of reading/writing head

As discussed in Section 4.5, the criterions in designing a reading/writing head for inherent storage applications within component surfaces are vastly different from those for hard disk drives. Even though high data density is important, stability of the reading/writing head as well as stored data precedes and is the most important design criterion. Unlike media employed in hard disk drive which are smooth rigid disks coated with a thin hard magnetic layer, media for inherent storage are relatively rough surfaces of components made from magnesium alloyed with ferromagnetic elements (Demminger, 2014). Furthermore, the reading/writing head is employed in production and maintenance environments which are hard to control and thus the head cannot be completely shielded from mechanical vibrations, stray magnetic fields and fine particle contaminations. A medium-head distance or a fly height is one of main parameters in a write process and need to be controlled preciously. Mechanical vibration causing small variations in the fly height thus highly affect the performance of the reading/writing system. Our first-generation head and its variant have a magnetic core made of MnZn-ferrite which is hard and brittle (Figure 6). Mechanical shocks, uneven surface components and dust particles can cause head collisions and damage. To circumvent this problem, the first-generation head evolves into the second-generation head which is flexible (Belski, 2013).
Coils on a magnetic core manufactured by wire winding are changed to planar coils fabricated by means of thin film technology. The second-generation head is immune to mechanical shocks; however, it

requires a precise formation of an air gap region and experiences high thermal load. In fact, only the air gap region, which can collide with a medium, needs to be flexible. In the next evolution step, the third-generation head has a more flexible magnetic core (Taptimthong, 2015).

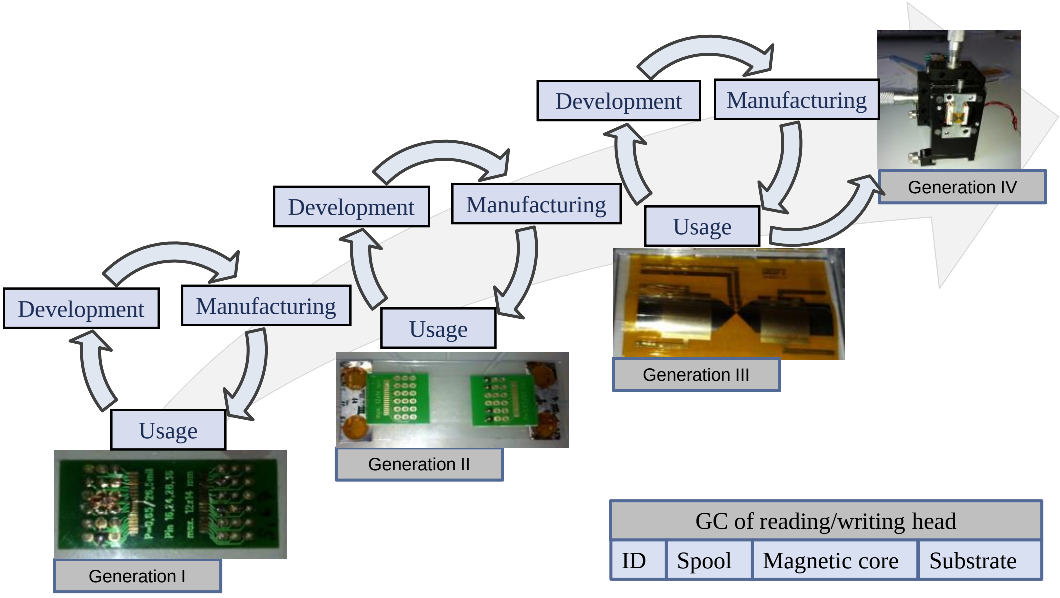

Figure 6. Evolution of Reading/Writing Head

This allows the air gap to be formed easily and it is possible to perform a write process in a contact mode eliminating the problem due to fly height variations. To increase data stability, a storage medium with higher coercivity should be used. As a consequence, the strength of the write field must be increased as well. However, due to the new head design, the maximum attainable field strength is quite limited. To write a high coercivity medium, the fourth head generation exploits heat-assisted magnetic recording (HAMR) to temporarily reduce medium coercivity during a writing process (Taptimthong, 2016). Through this long TI and development, many attributes of the head are improved or totally changed, while some are kept unchanged, e.g., the air gap length.

5 CONCLUSION

Storage and transfer of information identified during the lifecycle of the component is the cornerstone of the within CRC created approach called Technical Inheritance. Within this approach mechanisms of inheritance and information transfer in nature are considered and possibilities to adapt these mechanisms in relation to technical systems are studied. The advantage and one of the main purposes of TI is to create next generations of components, more adapted to the environmental requirements. The development and manufacturing of new generations is performed on the basis of purposefully collected information. The article identified and studied the main influencing parameter, which can be used as a basis of Genetic Code of components. A description of the standardized data exchange format is given for different phases of the component lifecycle. Technical Inheritance is exemplified at the development of several generations of an alloy with sensory properties which is used to design and produce smart components. A further example is given regarding the evolution of a device suitable for writing and reading of the GC of a component on its surface.

REFERENCES

Barton, S., Mroz, G., Reimche, W. and Maier, H.J. (2016), “Inherent Load Measurement and Component Identification by multi-dimensional Coded Data in the Component's Subsurface Region”, *Procedia Technology*, Vol. 26, pp. 537–543.

Belski A., Taptimthong, P., Wurz, M.C., Rissing L. (2012), “Integration of the Read-After-Write Method for Gentelligent Applications”, *Proc. 1st Joint International Symposium on System-Integrated Intelligence: New Challenges for Product and Production Engineering*, SYSINT2012: Garbsen, Germany, June, 27th - 29th, PZH Verl., Garbsen, pp. 49–51.

Belski A., Taptimthong, P., Wurz, M.C., Rissing L. (2013), “High permeability flexible bulk material for magnetic micro head applications”, *EPJ Web of Conferences 40*, 16003. DOI: 10.1051/epjconf/20134016003.
Cullity B. D., Graham C.D., eds. (2016), *Introduction to magnetic materials*. Hoboken, N.J.: IEEE/Wiley.
Demminger, C., Mozgova, I., Quirico, M., Uhlich F., Denkena, B., Lachmayer, R., Nyhuis, P. (2016), “The Consept of Technical Inheritance in Operation: Analysis of the Information Flow in the Life Cycle of Smart Product”, *Procedia Technology*, Vol. 26, pp. 79-88.
Demminger, C., Klose, C., Taptimthong, P., Maier, H.J. (2014), “Material-inherent Data Storage Using Magnetic Magnesium-cobalt Alloys”, *Procedia Technology*, pp. 188–197. DOI: 10.1016/j.protcy.2014.09.071.
Denkena B., Lachmayer, R., Ostermann, J., Nyhuis, P. (2016), “Datenaustausch in den verschiedenen Phasen des Lebenszyklus von smarten Produkten”, In: *VDI IT&Production*, Ausgabe 1-2.
Denkena, B., Mörke, T., Krüger, M., Schmidt, J., Boujnah, H., Meyer, J., Gottwald, P., Spitschan, B. and Winkens, M. (2014), “Development and first Applications of Gentelligent Components over their Life-Cycle”, In: *CIRP Journal of Manufacturing Science and Technology*, Vol. 4, Volume 7, Issue 2, pp. 139–150.
Feiste K. L. (2003), *Entwicklung der Harmonischen-Analyse von Wirbelstromsignalen zur Charakterisierung mechanischer Kugelgraphitgusseigenschaften*. VDI-Verl., Düsseldorf.
Friedrich H. E., Mordike B. L., eds. (2006), *Magnesium technology: Metallurgy, design data, applications. Berlin*, New York: Springer.
Gatzen H.H., Wu, K.-H., Traisigkhachol, O. (2006), “Development of a Recording Head for Magnetic Storage of Information on Machine Components”, *210th ECS Meeting*, Cancun, Mexico, October 29-November 3, 2006, pp. 191–202.
Gembarski, P. C., & Lachmayer, R. (2017), “Mass Customization und Product-Service-Systems: Vergleich der Unternehmenstypen und der Entwicklungsumgebungen”, In: *Smart Service Engineering* (pp. 214-232). Springer Fachmedien Wiesbaden.
Klose, C. (2014), *Entwicklung magnetischer Magnesiumlegierungen mit sensorischen Eigenschaften, Berichte aus dem IW*. Garbsen: TEWISS.
Klose, C., Demminger, C., Mroz, G., Reimche, W., Bach, F.-W., Maier, H. and Kerber, K. (2013), “Influence of Cobalt on the Properties of Load-Sensitive Magnesium Alloys”, *Sensors*, Vol. 13 No. 1, pp. 106–118.
Lachmayer, R., Mozgova, I., Reimche W., Colditz F., Mroz G., Gottwald P. (2014), “Technical Inheritance: A Concept to Adapt the Evolution of Nature to Product Engineering”, *Procedia Technology*, Vol. 15, pp. 178–187.
Lachmayer, R., Mozgova, I., Sauthoff, B., Gottwald P. (2014), “Evolutionary Approach for an Optimized Analysis of Product Life Cycle Data”, *Procedia Technology*, Vol. 15, pp. 359–368.
Lachmayer, R., Mozgova, I., Gottwald P. (2015), “Formulation of Paradigm of Technical Inheritance.”, *Proceedings of the 20th International Conference on Engineering Design (ICED15)*, Milan, Italy, Vol. 8, pp. 271-278.
Mróz, G. (2013), *Entwicklung von Techniken zur bauteilinhärenten Informationsspeicherung und Erfassung von Bauteilbelastungen*, Zugl.: Hannover, Univ., Diss., 2013, Berichte aus dem IW, Vol. 2013,4, PZH-Verl., Garbsen.
Sauthoff, B., Gembarski, P.C., Lachmayer, R. (2014), Der “Generative Design Approach”, in *Kontext von technischer Konfiguration*, *DfX 2014: Proceedings of the 24th Symposium Design for X*, October 1st-2nd, Bamberg, Germany.
Schumpeter, J. (2006), *Theorie der wirtschaftlichen Entwicklung.: Nachdruck der 1*. Auflage von 1912. Duncker & Humblot Verl., Berlin.
Taptimthong P., Düsing, J.F., Rissing L., Wurz, M.C. (2016), “Flexible Magnetic Reading/Writing System: Heat-assisted Magnetic Recording”, *Procedia Technology* 26, pp. 72–78. DOI: 10.1016/j.protcy.2016.08.011.
Taptimthong P., Rittinger, J., Wurz, M.C., Rissing, L. (2015), “Flexibles magnetisches Lese-/Schreibsystem: Design eines Schreibkopfes”, VDI-Gesellschaft Mikroelektronik, Mikrosystem- und Feinwerktechnik (Ed.), *MikroSystemTechnik Kongress 2015, MEMS, Mikroelektronik,* Systeme 26.-28. Oktober 2015 in Karlsruhe, 1st ed., VDE VERLAG, Berlin, pp. 684–688.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support from the Collaborative Research Center (CRC) 653 “Gentelligent Components in Their Lifecycle”, funded by the German Research Foundation (DFG). The authors would further like to thank all participants of the CRC and the Work Group Inheritance for their support, encouragement and implementation of various ideas.