Cyber Physical Gear Production System: A Vision of Industry 4.0 Gear Production

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Introduction

The engineering design print remains the dominating data storage medium for gear production. This is related to the genius Leonhard Euler, who invented the involute as an optimal gear profile. Involute gears can be accurately described using figures copied from drawings. During manufacturing, operators need to keyboard these figures several times into the machine controls. This is made possible by a bundled software system consisting of gear design and machine operation software, and quality inspection systems. But there as yet exist only a few interfaces for data exchange, and so the printed page continues as the primary data carrier on shop floors.

This report describes Klingelnberg's vision of Industry 4.0 gear production. It describes a concept for a gear production system called *GearEngine* that is fundamental to data collection during gear manufacturing. The system can be used to derive information from the data for process optimization and operator support. The main goal of the new system is quality optimization and cost reduction. The whole concept is based on Klingelnberg's philosophy that only an open system will be successful in the future. This means *GearEngine* is not limited solely to Klingelnberg products; it is also for machine tools from other machine tool manufacturers.

Figure 1 Leonhard Euler on the former 10 CHF bill.

The manufacturing principle of involute gears is based on a rack profile with straight flanks in mesh with a cylindrical gear. The rack profile is standardized according to DIN 867 (Ref. 1). The origin of this principle is Euler's (Fig. 1) invention of using the mathematical involute as a gear profile. The geometry of an unmodified involute gear is described explicitly if rack profile, dimension over teeth, helix angle, tooth width and tip diameter are known. Using involute gears as a standard gear profile does indeed have its advantages; however, that in fact is the reason why cylindrical gear manufacturing processes are so far removed from the principles of industry 4.0.

While the unmodified involute gear can be clearly described by some figures on a drawing, the descriptions of gears with lead and profile modifications are

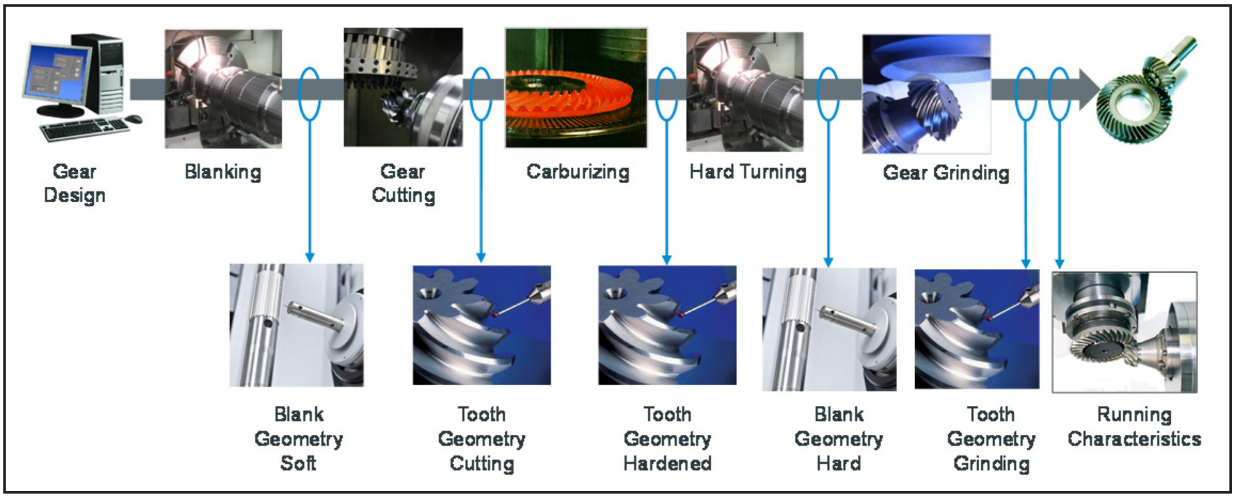

Figure 2 Creation of a digital twin in bevel gear production.

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Figure 3 **Klingelnberg Closed Loop 1.0.**

more complicated. Taking a lead crowning as an example, its value depends not only on the crowning — but also upon the length of the path taken for its evaluation (Ref. 2). This description of the cylindrical gear geometry via a few figures is not sufficient. An approach to make it more fail-safe is found in the standardized *Gear Data Exchange* (*GDE*) format.

But even with *GDE* the manufacturing of cylindrical gears remains far away from attaining the requirements of Industry 4.0. Industry 4.0 is linked to some buzzwords like "internet of things," "cyber physical systems" and "co-existence of virtual and real production systems;" they are just a brief example list of all terms mentioned in relation to Industry 4.0. Given its higher degree of complexity, Klingelnberg's bevel gear production system features digital twins and process models, i.e. — years closer to the requirements of industry 4.0 than the cylindrical production system. For Klingelnberg, the bevel gear production system is an example of the cylindrical production system of the future.

The design of bevel gears is based on material models that describe the load-carrying capacity of the basic material. The strength of the material was determined by standard tests on standard reference gear geometry. Thus the strength of the material must be adapted to the geometry of the individual gear. Therefore a standardized calculation model is available that is described in detail in Reference 3. The ISO standard is a virtual model that enables one to determine the running behavior of a virtual twin of the final part.

Industry 4.0 requires one single source of truth, which means information must be unique and have a direct link between sender and receiver; therefore Klingelnberg introduced one database for manufacturing. This database is installed at customer sites and all machines for gear manufacturing and quality inspection are linked to it. The design software is also linked to the database. For customers manufacturing gears at different plants, the database can be consolidated into one common database for all Klingelnberg machines at all affected sites.

The closed loop has been a part of bevel gear manufacturing systems for years. The actual gear geometry is calculated based on the virtual flank form description. Deviations from the target geometry can be traced back to machine settings that deviate from optimal machine settings. If the bevel gear production system is considered as an example for the cylindrical gear production system of the future, the implementation of a closed loop is the first step.

Implementation of Closed Loop for Cylindrical Gears

The first step in modernizing a bevel gear production system is to implement a digital data transfer between measuring center and gear grinding machines. This means that information described by figures must be transferred digitally to the operator software of the gear grinding machine. The implemented interface is based on the *GDE* format to enable an open interface that is not limited to Klingelnberg's *Gear Production* software.

The interface is available for involute gears of any type; thus internal and external gears can be evaluated and described by *GDE*. Important to consider is that gear quality can be evaluated according to different standards, but the geometrical deviation to the target is independent from this evaluation. This means the interpretation of the gear geometry must consider this; thus *Gear Production* deletes the *GDE* protocol (evaluation method) that was used during gear inspection — which prevents misinterpretation by the machine operator.

Who decides when a correction has to be calculated and the settings of the process must be changed? This question was also asked during the development of Closed Loop 1.0. Typically, it is the responsibility of the operator. But is it possible to provide some guidance? Can a company define general rules? Klingelnberg thinks it is necessary to define general rules and displays measuring results in *Gear Production* within tolerance fields (Fig. 4).

The customer can define green, yellow and red ranges for the tolerance field. The green area means the operator does not need to correct the process. The yellow fields display ranges where a correction is recommended. Red informs that the measured part was out of specification.

Closed Loop 1.0 is an active system, meaning that *Gear Production* alerts the operator if a new measurement for the running process becomes available. The operator acknowledges the alert and he is forwarded to the correction menu.

Calculation of Digital Twin

Closed Loop 1.0 is only one first approach to optimize cylindrical gear production. It is still not failure-safe because the operator might yet make mistakes by ignoring relevant measuring data. It is also not clear that the geometry that was considered in the gear design is really manufactured on the machine. In contrast to bevel gear

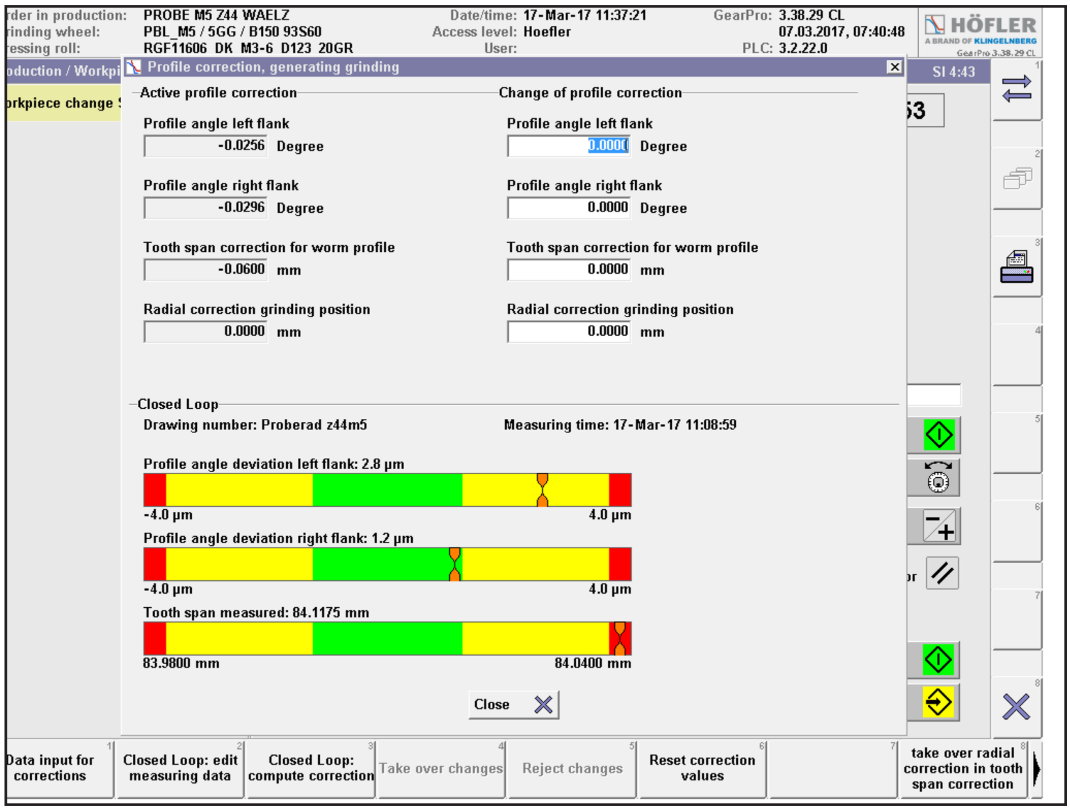

Figure 4 Illustration of measuring results in *Gear Production*.

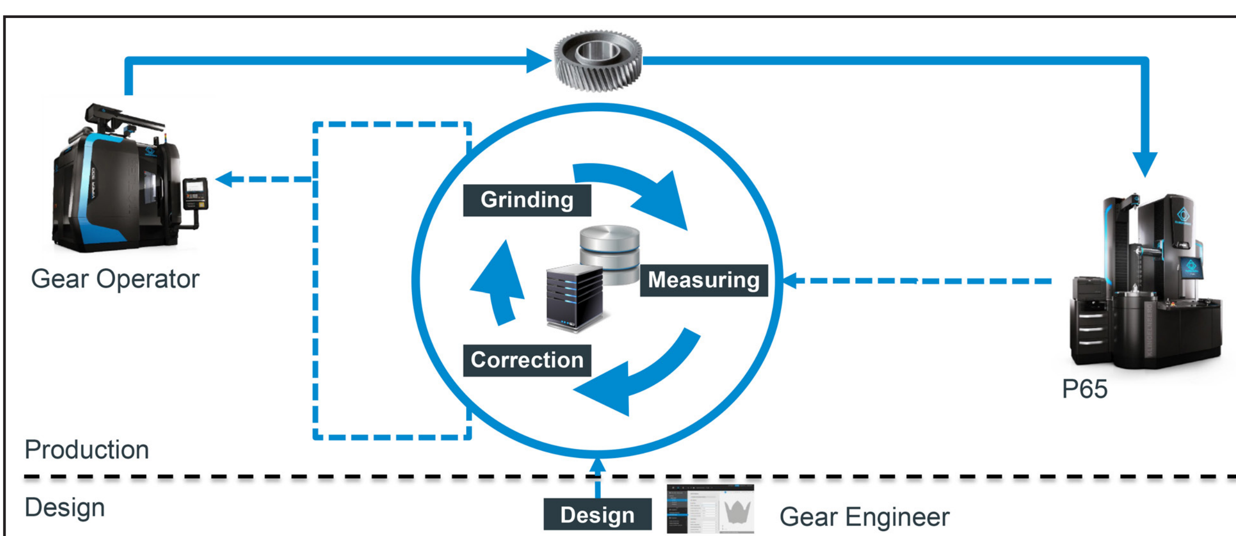

Figure 5 The new Klingelnberg Closed Loop.

production, the process simulation is not considered in the design phase. This may lead to different running behavior of the virtual twin and the manufactured gear. It also incurs higher costs in series production because tolerances are minimized in that the relevant deviation causing the different running behavior is not caused by the stability of the machine tool; it is related only to the process kinematics.

Klingelnberg decided to implement a quality gate in the gear design step, i.e. — to link gear design and gear manufacturing. The result is a software system called *Gear Designer*. As its name implies, the aim of this software is process design. It creates a virtual twin by process simulation. This geometry can be exported to the tooth contact analysis (TCA) software to determine whether the process-related deviation is acceptable or not. The designer also receives feedback to check how topological modifications affect productivity. This quality gate can be considered as a closed loop for the gear design phase. If prototypes are manufactured and tested as being good, the process can be frozen and passes the quality gate for serial production (Fig. 5).

Figure 5 describes a new closed loop with advanced functionality. The main difference to Closed Loop 1.0 is that the closed loop in series production is based on an approved geometry derived from a manufacturing simulation. This means the target geometry used for the correction is a real virtual twin — comparable to the target geometry used for bevel gear manufacturing. Should deviations from the target design be detected, they can be completely compensated for by the process.

Virtual Process Design is an Enabler of Silent Gears

Gear design has three main targets — the gear set must fulfil requirements on load-carrying capacity, efficiency, and low noise; the last requirement is checked by subjective noise evaluation. The driver of the car evaluates the noise by NVH rating. Generally there is no sophisticated calculation model available that synthesizes the final noise based on the gear set excitation.

In future, the requirements of noise quality will increase. Urbanization, demographic change and climate change will lead to a rising demand for gears in noise-critical applications. Electric-driven cars are one of the most sensitive applications for gear noise. The input speed of the transmission can exceed 30,000 rpm and the masking noise from the combustion engine is missing. But also e-bikes, trains, etc., are noise-critical applications.

If the gear process is simulated in the gear design phase, the designer can then use the real geometry for TCA. Christian Carl presented at the International Conference on Gears in 2013 (Refs. 4–5) an approach for gear noise synthesis based on a dynamic gear mesh simulation model. He demonstrated that there is good correlation between tooth contact analysis and gear noise. As long as the real tooth geometry is considered during gear design, a comparison between different gear designs is possible. Also, if the effort for simulation is reduced by testing gears in situ, a good gear design can be determined. As long as the manufacturing can ensure that the geometry is equal to the approved geometry, the risk of unforeseen gear noise will be reduced.

A Vision of Industry 4.0 Gear Production

What gear manufacturers gain from series production is information that results in realistic tolerances for gear design. This information is also needed for later failure analysis if problems occur in the field. Data collection and analysis are also needed for quality improvements,

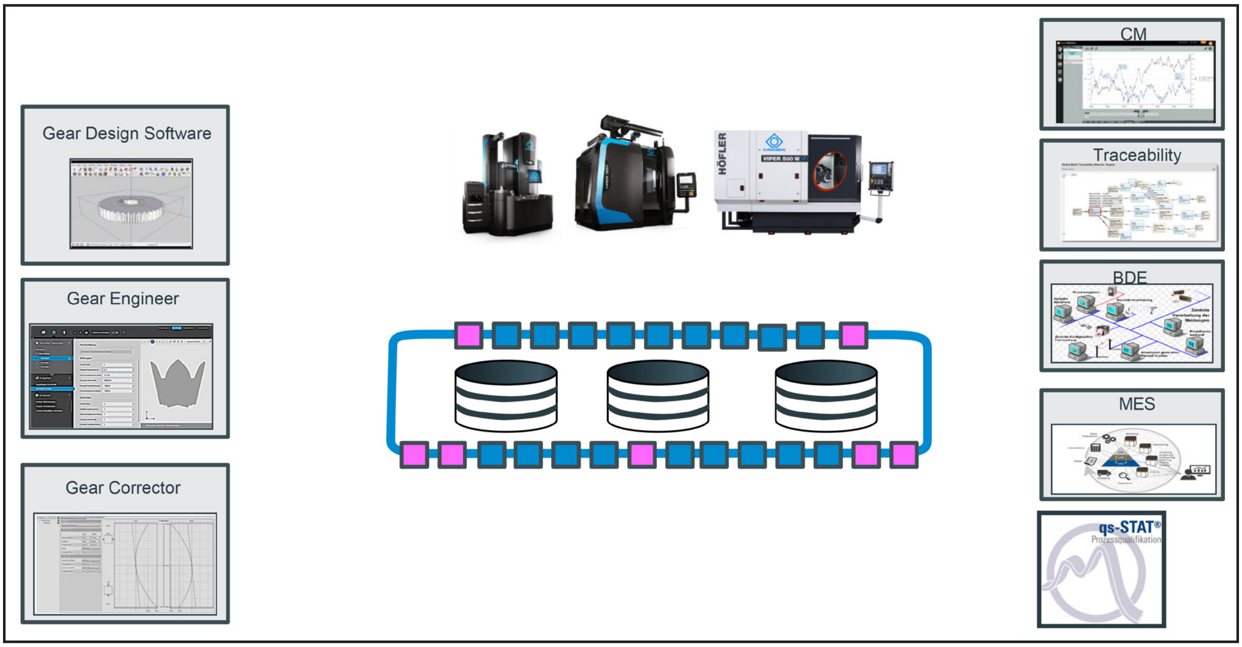

Figure 6 Klingelnberg *GearEngine*.

process optimization, tool life analysis and continuous improvement processes. Gear manufacturers continue to use disparate software solutions and enterprise resource planning (ERP) systems to collect data from production. Machine tool manufacturers must create individual interfaces for every type of machine in the field. All interfaces must be updated continuously and this need expands with every sold machine.

Klingelnberg has created the concept of a new production system for gears — *GearEngine*. The heart of *GearEngine* is a database for gear data, tool data and production data. The platform has interfaces to design software for gear and process design (e.g., *Gear Designer*). Every machine in the production network is connected to *GearEngine* and is reading and writing data. This means that data is not stored locally on machining centers — it is *centrally* stored in *GearEngine*.

GearEngine is an open system; new applications can be programmed not only by Klingelnberg but also by customers and partners. The stored data in the system can be used to improve the set up process, to create new knowledge for the gear design, or for predictive maintenance. It is not limited to cylindrical gear production. In future all Klingelnberg products will be integrated into *GearEngine*.

Summary

Klingelnberg's new *GearEngine* is the consequent follow-up to Klingelnberg's Closed Loop 1.0. It contains functionality like the new Closed Loop for cylindrical gears. Software products like *Gear Designer* and *Gear Operator* are integrated, as are Klingelnberg measuring centers. The heart of the system is a database for data storage. Open interfaces to other applications are needed to add continuously new functionality to it. *GearEngine* is a platform that readies gear production for Industry 4.0.

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Markus Brumm, a RWTH graduate with a degree in mechanical engineering, began his career in 2005 as a research assistant in gear investigation at the Laboratory for Machine Tools and Production Engineering (WZL) of the RWTH Aachen. He subsequently became that group's team leader in 2010.

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