Sustainable Production of Sanitaryware by Digitalization of the Firing Process

G. Seifert, T. Agné, M. Gebert, M. Nause, Ch. Winter

The sustainability of high temperature processes is a key issue on the way to a decarbonized circular economy. Digitalization of the processes offers a good opportunity to immediately improve energy and material efficiency without the need for major investments in new production kilns. In this context, an ongoing joint project of three companies and one research partner is devoted to the development and application of digital technologies to make the production of large and complex ceramic products significantly more sustainable. The concept and current status of the project, which is focused on sanitaryware as a prototypical example, is described.

1 Introduction

The manufacturing of sanitaryware is a prototypical example for the growing complexity in contemporary ceramic production and the resulting challenges for producers. Modern customers have a strong desire for aesthetic design and innovative functionality, leading to sometimes very sophisticated design challenging for both the material properties and the production process. Fig. 1 gives two examples for current high-level sanitary products of Villeroy & Boch AG. Subway 3.0 boasts a timelessly beautiful design combining deep wash basins and side ledges for maximum comfort and toilets flushing very thoroughly while saving water with the new TwistFlush technology. Furthermore, excellent shape accuracy is needed for integrating the products into modern bathroom furniture. In the course of understanding sanitaryware as design elements it is essential that the products are perfectly free from any visible defects.

With this background, it is an evident challenge to design and maintain a sustainable production, when even minuscule deviations from the design geometry or tiny inclusions visible on the product surface regularly make products unsalable. As a consequence of these market requirements, a certain percentage of products currently has to be either locally repaired and sent through a second firing process before sale, or even be declared as deficient. In both cases, the strict selection criteria cause a tremendous waste of energy, in the second case also of raw material resources. It would therefore be highly desirable to develop the current production further into an optimized process releasing every single product absolutely flawless. At the same time, this would make production much more sustainable by minimising energy and raw material con-


Fig. 1 V&B wash basin FINION (l.) and V&B WC bowl TwistFlush (r.)

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sumption. In that sense, one research and three industry partners (Fraunhofer HTL, Villeroy & Boch AG, Keramischer OFENBAU GmbH, Meprovision GmbH) joined forces in a R&D project funded by BMWK[1)] to develop and demonstrate innovative digital technologies for increasing the sustainability of producing large ceramic products. In the project with the acronym HTPgeox[2)], several digital techniques from material-specific thermal process simulation to individual tracking, monitoring, and evaluation of the kiln history of every single product are being developed and applied to the sanitaryware production of Villeroy & Boch as examples for large and geometrically complex components. This article will present an overview of the project concepts, current achievements at halftime of the project work and perspectives for the project completion and beyond.

2 Concept and goals of HTPgeox

The energy efficiency and sustainability of a production requiring high-temperature processes can be tackled from two different sides: firstly, it is an apparent approach to try to minimise the energy consumption and carbon footprint of the industrial kiln used in the production process by optimizing combustion, minimising thermal losses through kiln walls, or implementing energy recuperation. While ambitious concepts for dramatically reducing the energy consumption of, e.g., tunnel kilns have already been elaborated theoretically [1], their implementation will take decades rather than years, considering that large industrial kilns are usually operational for 30 to 40 years.

Therefore, HTPgeox takes a different view focusing on material- and product-related digitalization techniques for immediate increases in sustainability, which can be implemented in existing kilns without large investments.

Roughly spoken, the production of sanitaryware (as an example), which in the case of Villeroy & Boch is already featuring a high degree of digitalization through many production steps, shall be fully transferred to the industry 4.0 standards by including firing processes into the digitized production chain. One obvious obstacle to this goal are the high temperatures above 1000 °C, which discourage the use of any active electronic components monitoring the current position and status of the products within the kiln. Instead, several techniques for passive or indirect monitoring of each product's kiln history are being developed or adapted in the project. Plus, predictive modeling of the material and component behaviour depending on the firing curve and specific kiln situation is a key element of the concept.

The common goal of all digital technologies under development in HTPgeox is, firstly, to understand in detail how the individual thermal treatment of a product on its way through the tunnel kiln, including its specific setting on the kiln car, affects the final product properties; then, secondly, the information shall be used to develop and implement an optimized control of the thermal process – including product positioning on the kiln car – which enables a waste-free, energetically optimized production.

The material-specific approach used in HTPgeox is the well-established, unique predictive thermal process simulation of Fraunhofer HTL, which is strictly based on precise in situ experimental characterisations of the material's process kinetics such as debinding, dehydration and sintering [2, 3]. The technique enables assessing all potentially deleterious effects of the thermal treatment of products, such as:

- internal pressure buildup due to thermally activated emanation of gaseous products,
- temperature gradients and resulting internal mechanical stresses due to the complex geometric shape of a product,
- temperature gradients and resulting internal mechanical stresses due to inhomogeneous heat transfer in dependence of the concrete kiln situation,
- incomplete and/or inhomogeneous sinter shrinkage (leading to shape deviations of the final product) resulting from an improper heating curve or unfavourable heat input.

Due to these features, the numerical modeling is being used in the project for (i) determination of material-specific firing curves optimized for minimum energy consumption, and (ii) for detailed analysis of potentially kiln-related product flaws and development of strategies to remedy them.

A second key element in the concept is a continuous monitoring of kiln and product data with the goal of tracing back the kiln history of every single product. When this monitoring is set up and tested, the goal is to register a continuous data flow containing at least the product code, product position and orientation on the specific kiln car, characterisation of final product quality and a timeline correlating all available kiln parameters to the current position of the kiln car.

Detailed analyses of these data, as explained in more detail below, will then be performed in the project and thereafter for identifying and avoiding kiln-related quality problems.

Development and testing of the data monitoring during the kiln cycle itself is done in the project in close cooperation of Villeroy & Boch and Keramischer OFENBAU, since the latter have constructed and built the tunnel kiln under consideration in the V&B site at Mettlach/DE. The company Meprovision is responsible for developing an automatised optical registration of product type and positioning on the kiln car before entrance into the kiln. Such an automatic, obligatory acquisition of product positioning is of great importance for the project, because in the current production product types as well as materials are mixed on every kiln car, and human operators are free to distribute the different components on the kiln car in patterns based on their experience.

This procedure is beneficial for the project, as it creates a broad variety of setting patterns which in turn should enable identifying and understanding all relevant problems due to product positioning or deviations of kiln parameters. Prospectively, however, the project results will be used to develop guidelines for preferable patterns on the kiln car as aid to the operators and, on the long run, to establish a fully automatised setting process considering all the knowledge acquired about a firing process optimized with respect to both energy efficiency and product quality.

To gain full benefit from the acquired data, it is essential to conduct in-depth analyses of correlations between kiln situation and product quality, as well as to look for self-learning algorithms which can prospectively

[1)] German Federal Ministry for Economic Affairs and Climate Action – Bundesministerium für Wirtschaft und Klimaschutz

[2)] The acronym HTPgeox stands for (optimization of) High Temperature Processes for large and geometrically complex ceramics be integrated in automated kiln control. Within the project, the first approach to finding relevant correlations was manually recording relevant data of products on several randomly selected kiln cars. Fig. 2 shows an exemplary kiln car loaded with several wash basins and toilet bowls. Additionally, identifying product flaws and looking for plausible technical and physical reasons was initially attributed to the judgement of experienced personnel.

The second approach, which will be the preferred choice as soon as the regular acquisition of product and kiln data during standard production is fully operational, is the application of Artificial Intelligence (AI) algorithms for finding correlations autonomously. For both approaches, the process simulation of Fraunhofer HTL will be utilised to investigate if a quality problem can safely be attributed to a specific thermal transfer problem caused by product positioning or deviations of a kiln parameter from its setpoint value. Once acquired, such an in-depth insight will be used to develop strategies to abandon the source of product flaws.

Finally, data safety and company-independent data handling is an important issue as well. Considering that a kiln provider like Keramischer OFENBAU usually has delivered many similar or even identical industrial kilns, it will be beneficial if they gather and evaluate the empirical data from all "their" kilns. Such a centralised approach promises to generate a much broader knowledge base for advanced kiln control than just the observation and evaluation of a singular kiln.

Therefore, it is also part of HTPgeox to develop suitable concepts for such a comprehensive data acquisition, which includes the reverse way of providing immediate responses to local operators in case of kiln irregularities.

3 Current achievements and future perspectives

In the ongoing project, after about half of the scheduled development time of three years, good progress on the way to the ambitious goals has already been achieved. In situ characterisation of several ceramic materials for different sanitaryware has been acquired as a basis for the predictive simulation of component behaviour in the kiln. The process kinetics of, e.g., dehydration or sinter shrinkage, as measured by using several different heating rates, is input to FE process models in form of a so-called kinetic field [4].

Fig. 2 Example for a kiln car loaded with six wash basins and six WC bowls

With these predictive models, the shortest and most energy-efficient temperature cycles to achieve the required final product density and shape can be identified on the computer. Fig. 3 shows an example for simulated sintering of a wash basin from the product program of Villeroy & Boch. Colours refer to different sinter density achieved due to the assumed (unfavourable) situation of thermal transfer.

On the way to monitor and identify kiln-related quality problems, a set of over 700 products on 46 kiln cars from the regular production has been manually documented and analysed. The positioning on the kiln car was in that case only monitored in a coarse grid including the product orientation with respect to the travel direction through the tunnel kiln (forward, backward, left, right). A clear finding even from this small number of samples was that toilet bowls set in backward orientation show a significantly increased probability for cracks. While in this case the perception of the problem is as easy as its remedy is straightforward, several further tentative findings need, firstly, much more data to be statistically relevant and, secondly, an in-depth, simulation-assisted analysis to derive the optimum strategies to avoid pertinent product flaws.

For the next iteration of this monitoring and analysis, an optical detection system will be installed. Meprovision has meanwhile tested several technically different commercially available systems with the result that a time-of-flight detection system using infrared pulses features the best cost-performance ratio for the required task: iden-

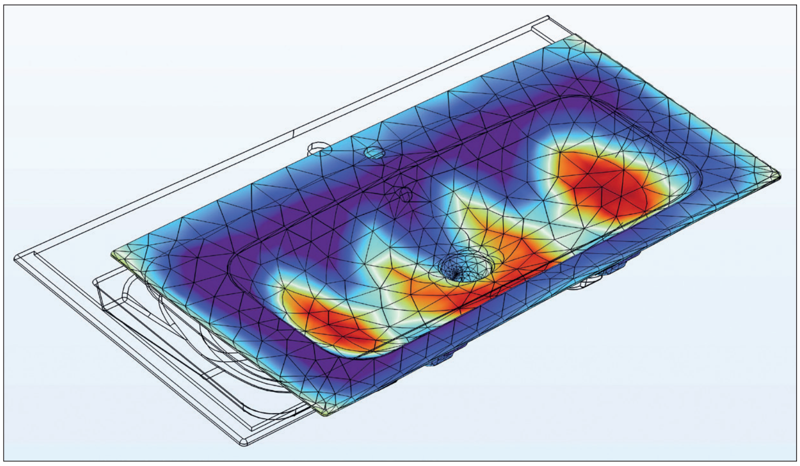
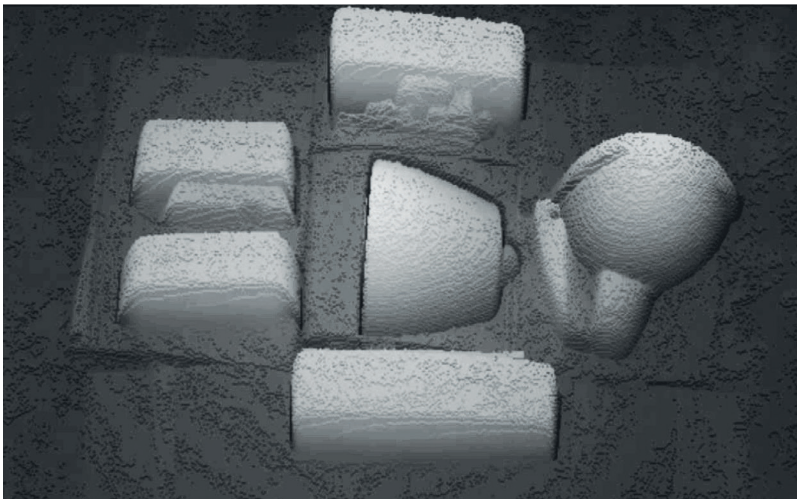


Fig. 3 Example for a 3D sinter simulation of a wash basin



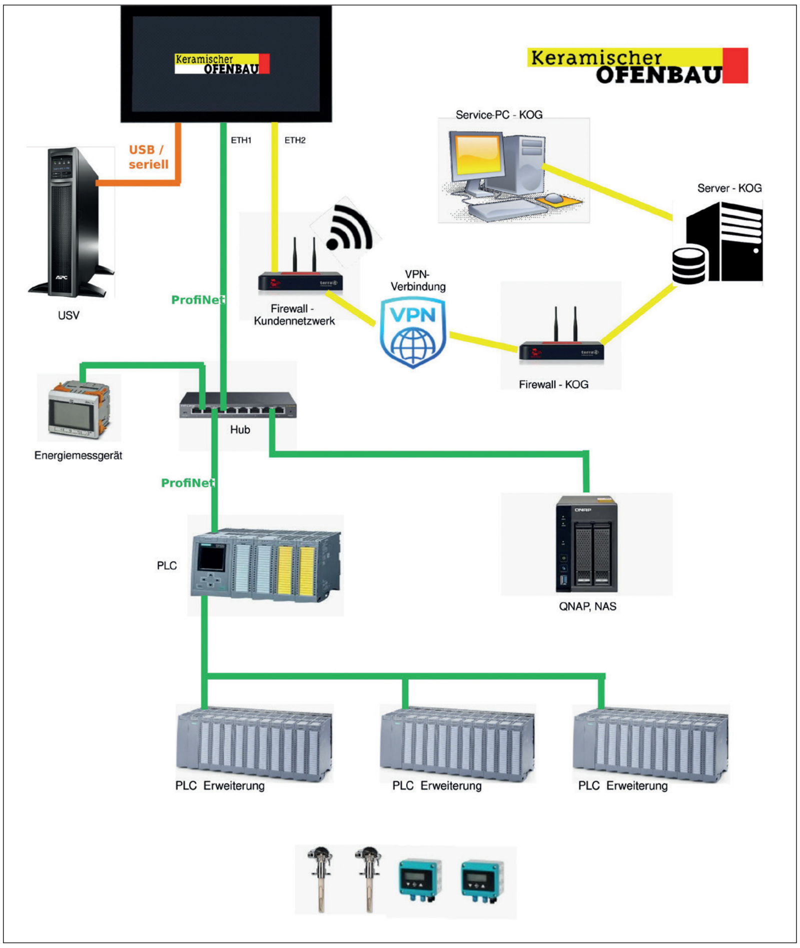


Fig. 5 Schematic overview of data transfer between the kiln control system and the KOG servers

tification of the products by means of their 3D shape and defining their position and orientation on the kiln car with a limited resolution of about 1 cm. Fig. 4 presents an example for a Time-of-Flight (ToF) image of a few products arranged stochastically. A software to extract the relevant product positioning data is under development.

Looking for the products' kiln history, it is essential to know, as a function of time, the temperature cycle they have experienced on their way through the kiln. Since in a tunnel kiln the temperature sensors are mounted at fixed positions, a method was developed to generate time-temperature curves for each kiln car by assigning the appropriate local sensor value to the current kiln car position based on the exact time of kiln entry and the current velocity of the transport system.

The resulting curves are in perfect accordance with the data of a special thermocouple car, which so far is sent through the kiln periodically. Therefore, along with the temperature, further data like the (local) amount of gas and air used for the burners can be assigned to any point of time within the thermal process cycle of each product, enabling well-adapted simulations of the thermal situation of a product in a specific kiln segment. Such simulations will be used to analyse thermal transfer problems relevant for product quality in detail.

Finally, a concept for safe data transfer from the kiln control system to a service provider (like Keramischer OFENBAU) has been developed, installed, and tested. A schematic overview of the system is given in Fig. 5. In the left part of the figure, the company network of the kiln user (green connections) is shown enabling to locally analyse, visualise and save the multiple process data from the Programmable Logic Control (PLC) of the thermal process system.

The yellow data path realised via a secure VPN connection enables an external service provider to perform additional continuous data analyses as well as giving immediate feedback to kiln operators in case of unexpected difficulties. If the service provider is also a kiln manufacturer, he can set up a broad knowledge base derived from the performance data of many kilns, enabling reasonable advice also in case of problems being new and unexpected to the specific kiln.

Overall, the results obtained in the project HTPgeox so far already clearly show that the methodology of digitizing the kiln process of sanitaryware has a high potential to immediately improve the sustainability of production significantly.

First, the material specific process simulation of Fraunhofer HTL, which has been set up during the first project phase, will be applied to find the most efficient firing curve(s). Based on the experience of previous projects using this simulation concept, the implementation of these optimized firing cycles indicates a reduction of the total energy needed per final product by at least 10 %. An additional reduction of similar magnitude can be expected when the continuous monitoring of each product's kiln history has been evaluated for a considerably large number of samples, and the insights about kiln- or positioning-related product faults are implemented to avoid the majority of such flaws. As far as severe quality problems are concerned necessitating individual products to be considered as rejects, the implementation of the project results will also contribute to resource efficiency. With the continuous monitoring there is also a chance for further improvement of sustainability in the future and, probably equally important, a means to quickly and flexibly adapt sustainable firing conditions to new products.

4 Summary and outlook

In this paper, an overview of the technological concepts for digitalization of the firing process of large and geometrically complex ceramic products, being developed in the joint project HTPgeox, has been given. The project concept comprises material-specific process simulation, continuous monitoring of kiln process and firing results including automatic optical registration of the product positioning on the kiln car, documentation of the kiln history of each product and AI-based correlation of product quality and kiln history. It has been demonstrated that the combination of these technologies might increase the energy efficiency of the production by up to about 20 %, complemented by an increase of material efficiency via avoiding deficient products. The implementation of these digital technologies will in future also considerably facilitate the introduction of new products or materials as they enable quick and widely automatized adaptation of thermal process conditions, thus keeping the production's sustainability at least at the achieved level.

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