Inline Quality Monitoring and Data-Based Quality Prediction

Successfully Managing Digital Transformation with Automation and Artificial Intelligence

Maintaining competitiveness while producing in Germany requires not only cost-efficient production, but also high-quality products. Vorwerk Elektrowerke is accepting this challenge. In collaboration with the Institute of Product Engineering at the University of Duisburg-Essen, Germany, the company is testing a 100% inline quality monitoring system as well as a quality prediction using machine learning.

The Vorwerk Elektrowerke GmbH & Co. KG manufactures high-quality household appliances that are known worldwide under brand names like "Thermomix" and "Kobold". Since these are primarily located in the upper price segment, customers have correspondingly high demands on product quality. These are reflected in the quality requirements that apply to the molded parts used. These are produced in three shifts at the Wuppertal plant in Germany, the largest production site of the Vorwerk Group, mainly by injection molding.

Production at the high-wage Germany generally requires continuous innovations in the field of process technology in order for the company to remain competitive in the long term, both in terms of quality and cost aspects. Within this context, Vorwerk has decided to work together with the Institute for Product Engineering (IPE) at the University of Duisburg-Essen to investigate the added value of optical 100% inline quality assessment and direct prediction of molded part quality based on process data for injection molding production.

Tightness as the Ultimate Goal

The first step was to select a suitable molded part. The choice fell on the filter cover of the Kobold VK200 vacuum cleaner (**Title figure**). This is made of acrylonitrile-butadiene-styrene (ABS) and has a sealing lip made of a thermoplastic elastomer (TPE). The filter cover (**Fig. 1**) is produced on a hydraulic two-component injection molding machine (type: 500–2000–180-CX Z; manufacturer: Krauss-Maffei Technologies GmbH, Munich, Germany).

In addition to the assembly capability and an optically perfect surface of the molded part, the sealing effect of the sealing lip is of great importance. Otherwise, the function of the vacuum cleaner would be affected, and the customer would be bothered by unwanted background noise when air flows through the sealing area. Two things are necessary to ensure the sealing effect:

- The complete forming of the sealing lip and
- the accurate, circumferential position of the TPE contour.

The latter is directly related to the molded part contour of the hard component, which is represented by two width dimensions and should be the focus of this investigation.

Inline Assessment of the Molding Contour

A digital camera system (type: CV-X; manufacturer: Keyence Deutschland GmbH, Neu-Isenburg, Germany) was used for the trial (**Fig. 2**). As no color information is required for recording the molding contour, a monochrome sensor came to use. In order to be able to map the variation in width dimensions suf- »

Customers who choose the Kobold VK 200 vacuum cleaner expect top quality. To ensure this, efforts for the introduction of Industry 4.0 measures are taken in the production plant in Wuppertal, Germany © Vorwerk ficiently accurately, the highest-resolution sensor in this model series was chosen, with 21 megapixels. The entire camera system was integrated into the existing process both in terms of hardware and software by Mabri.Vision GmbH, Aachen, Germany.

The molded parts are photographed immediately after removal, while they are still in the robot's grip. Therefore, the handling robot sends a trigger signal to the camera control. Afterwards, the molded part is fed to the assembly line via an automatic conveyor system. Over an investigation period of around four weeks, more than 22,000 molded parts were produced, and their quality parameters recorded as described above.

Fig. 1. The contour of the molded part is crucial for the functionality of the sealing lip (TPE) of the filter cover © IPE

Maximum Usability

Overall, the system proved to be very robust. It is designed in such a way that it automatically starts when the robot is switched on and records the quality of all parts produced from then on. The molded part dimensions extracted from the recorded images were defined once, then automatically recorded and provided with a time stamp. For trouble-free further processing, it is therefore important to synchronize the times of the injection molding machine and the camera system. This can be ensured in the case of permanent use by connecting the system to a time server through connection to the company network.

Within the scope of optical quality monitoring, two width dimensions are recorded for fundamental testing. These are determined as the maximum perpendicular distance from the middle partition of the molded part to the outer contour and are referred to in the following as dimension 1 and dimension 2. The total width of the molded part is the sum of the two individual dimensions. By recording the individual dimensions, statements can be made about possible asymmetrical warpage of the part in addition to the overall width, which is equally relevant to quality.

In addition to the inline quality monitoring described above, the project team investigated whether the quality parameters under consideration can also be predicted indirectly – i.e. without measurement – from the process data stored in the actual data log of the injection molding machine. For this purpose, methods from the field of machine learning are used, which is a sub-area of artificial intelligence. Although this topic has already been investigated in the past [1–4], available applications [5] have so far hardly been able to establish themselves in industry.

Machine Learning for the Prediction of Quality Features

Based on many years of experience in the analysis of injection molding process data, the IPE researches the various aspects relevant for molded part quality prediction. The aim is to create a holistic system that performs all necessary data processing steps automatically [6] and therefore enables the user to handle the system easily (**Fig. 3**). The procedure comprises in detail:

- Data pre-processing,
- feature construction and selection,
- modeling and hyperparameter optimization,
- model selection and quality prediction with the best model, as well as
- model adaption in case of changed process conditions.

The data preparation (standardization, etc.) required for proper processing is followed by the construction and selection of the process features used as input for the quality prediction, the first central step for a successful prediction [7]. Own investigations [8] have shown that a filter-based approach with sequential forward selection as search strategy and correlation-based feature selection [9] provides the best results in injection molding.

Seven "state of the art" learning algorithms from the field of supervised learning are used for the actual modelling. In addition to well-known algorithms such as artificial neural networks, e.g. Support vector machines and Gaussian process regression are included. These are trained in parallel as part of the overall system and compete against each other – only the model that achieves the best performance on the validation data is finally used for the prediction.

To ensure that the individual learning algorithms reach their maximum performance, the respective hyperparameters that control the model structure and learning process are automatically optimized during modeling. Through production, the relationships between process and quality parameters can change, which reduces the quality of the prediction. This can be recognized by methods which can detect so-called concept drift, which also were implemented. The IPE was able to design the prediction system in such a way that operation on a desktop PC of the current generation is possible with reasonable computing effort.

Bild 2. The CV-X camera system used has a monochrome sensor with a resolution of 21 megapixels © Keyence

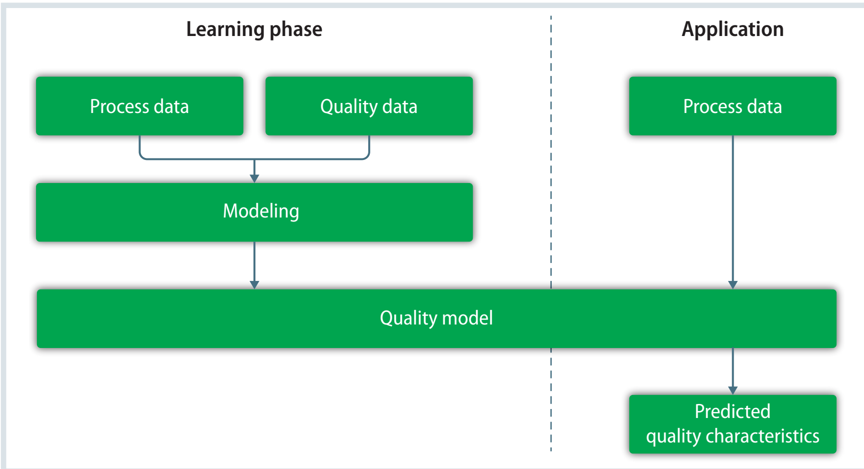

Bild 3. The automatic model generation relates to only little effort for the user: once the learning data has been provided, everything else runs automatically Source: IPE; graphic: © Hanser

Reliable Performance

To evaluate the quality prediction, a design of experiments (DOE) covering 75 injection molding cycles was carried out in addition to the approximately 22,000 cycles from series production. The following machine setting parameters, selected based on experience, were varied within the scope of the DOE:

- Injection speed of the hard component (ABS),
- holding pressure level of the hard component,
- cooling water temperature,
- cooling time.

Because of the lower number of cycles in the DOE, it was possible not only to assess the quality features with the inline camera, but to manually measure with a gauge specially manufactured for this molded part, which is also used in normal serial production. This allows a comparison of how well the quality data generated with both measuring methods are suitable for modelling. It must be considered that the shrinkage of the molded parts is not yet completed at the time of recording with the camera system, so that there is a deviation from the final dimensions.

It should be noted that modelling is generally also possible based on historical process and quality data. The former is continuously recorded in any case by the injection molding machine. However, the condition is, that the quality data is assigned to the exact process cycle.

The coefficient of determination is used to evaluate the models. This can achieve values between 0% and 100% and indicates the degree of overall variance of the quality feature described by the model. The results show that a quality prediction with coefficients of determination of up to 98.8 % is generally very well possible (**Fig. 4**).

In the DOE, the model performance based on the camera data with coefficients of determination between 95.7% for dimension 1 and 98.8% for the total width are slightly above the model performance on the basis of the gauge data with 87.8% for dimension 1 to 93.6% for the total width. The coefficients of determination for the prediction of dimension 2 lie in between. However, all these model performances can be classified as satisfactory.

Autonomous Processes, Low Reject Rate

In serial production, however, the coefficients of determination of the two partial widths (dimension 1 and dimension 2) are significantly below the coefficient of determination of the overall width. The latter has a very high model performance of 90.0%. As a further analysis showed, the low coefficients of determination of the part's partial widths (12.6% and 18.1%) are due to an insufficient accuracy of the camera system when recording the position of the middle rib, used as a reference. This occurs when the alignment of the part on the gripper is subject to fluctuations around the vertical axis and could be remedied by adjusting the measuring system.

Company Profile

The **Vorwerk & Co. KG** was founded in Wuppertal, Germany, in 1883 and has developed from a carpet factory into a broadly-based international group of companies in the course of its more than 130-year history. Vorwerk's core business comprises the development, production and sale of high-quality household products. Vorwerk Elektrowerke is part of the family-owned company that employs a total of more than 12,300 permanent staff. As the largest production location of the group with its headquarters in Wuppertal, Vorwerk Elektrowerke manufactures high-quality household appliances such as the multi-functional Thermomix food processor or the Kobold vacuum cleaner.

corporate.vorwerk.com

Bild 5. Continuous quality monitoring as a must, autonomous process control as freestyle – plant manager Dr.-Ing. Markus Koch is satisfied with the investigations

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Since the errors of the partial widths cancel each other out exactly, the overall width is unaffected. In the case of the DOE, this problem has hardly any negative effect, due to the variation of the machine settings, the part's real variation outweighs the measurement uncertainty. Overall, it can be stated that modelling is also possible on the basis of data from series production, as long as there is sufficient measurement accuracy.

All in all, the conditions for the future use of the technologies investigated are very good, says plant manager Dr.-Ing. Markus Koch (**Fig. 5**): "Competitiveness in Germany as a high-wage location can be achieved if the autonomy times of manufacturing processes are high and therefore employee deployment is low. If this succeeds with low reject rates, as is the case with permanent quality monitoring, the duty is fulfilled. The freestyle is achieved when process adjustments can be made depending on quality deviations without the need for manual intervention."

Conclusions

With the investigation of the inline camera system and the model-based molded part quality prediction, Vorwerk Elektrowerke decided to actively shape the digital transformation and thus secure its competitiveness in the long term. The camera system proved to be easy to operate and very robust over the test period. The testing of the quality prognosis system was also successful. The high model performance shows that it is possible to make a good prediction of the quality characteristics of molded parts. However, this requires a high accuracy of the quality data used in the learning phase. ■

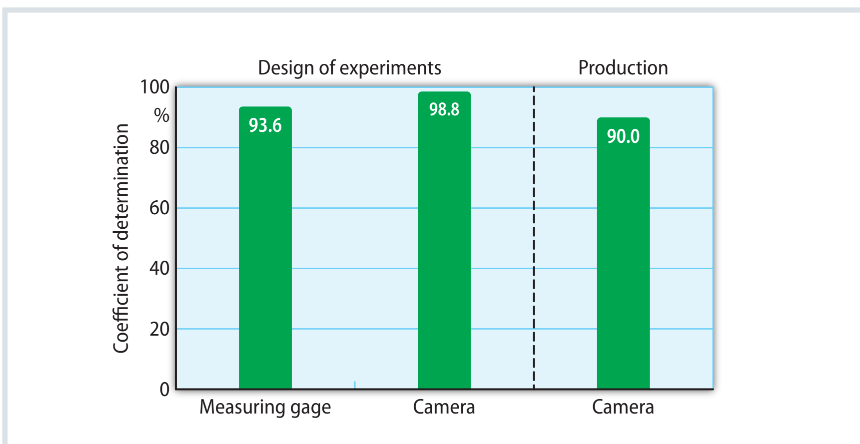

Bild 4. The achieved model performances show that a prediction of the quality characteristics based on the process data is well possible. The requirements for this are precise quality data

Source: IPE; graphic: © Hanser

The Authors

Alexander Schulze Struchtrup, M.Sc., is group leader injection molding since 2018 at the Institute of Product Engineering (IPE) at the University of Duisburg-Essen, Germany;
alexander.schulze-struchtrup@uni-due.de
Dipl.-Ing. Alexander Mahl is a project engineer in plastics technology at Vorwerk Elektrowerke GmbH & Co. KG since 2015.
Dimitri Kvaktun, M.Sc., is a research associate since 2019 at IPE.
Dipl.-Ing. Martin Thalemann is group leader plastics technology at Vorwerk since 2015.
Prof. Dr.-Ing. Reinhard Schiffers is holding the chair for Engineering Design and Plastics Machinery since 2017 at IPE.

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Service

References & Digital Version

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