

# Q-Guard - An intelligent process control system

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## Q-Guard – an intelligent process control system

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**Abstract.** Stainless steel is a complex material and has properties that make it difficult to use in deep drawing processes. Because of its scattering material properties a robust process is difficult to achieve, resulting in the necessity to constantly adjust the drawing process. In order to produce parts at constantly high quality and to minimize scrap production, an intelligent control system, the Q-Guard system is implemented in production, covering the whole process chain from raw material to the finished part. This control system is presented in this contribution, with the main focus on the process control. This system is based on numeric simulations as well as material data, the process settings and draw-in measurements, all of them acquired in-line in production. Part of the data is used for a feedforward control for immediate good parts production, part of the data, like the draw-in, measured with an optical measurement system after the first draw, is used in a feedback loop. The layout of the process control and results from production runs will also be shown in this work.

### 1. Introduction

Cost pressure in modern industry forces companies to utilize all possibilities to increase efficiency and reduce production cost. This goal in mind, the Q-Guard system was developed and implemented in production. This system is based on robust process design combined with the in-line acquisition of all relevant parameters and a process control of the forming process. Therefore each part has its own unique set of data and can be identified through a marker for continuous retraceability. In order to improve process design for new products, all data recorded in production are stored in a database for later use.

Due to the complex shapes modern processes are extremely sensitive to even small variations of the process parameters (e.g. material, friction conditions) [1]. This is especially evident in the forming of metastable stainless steels, since their Martensite forming behavior has a big impact on the process and



part quality. For such processes, standard methods like six sigma to improve process robustness and quality in production also meet their limits [2]. For these reasons a process control is a viable approach to achieve a robust process and reduce scrap production. In the case of deep drawing processes, such a control system can be integrated in the stamping line to adjust the blank holder force [3].

In the past, several attempts to control deep drawing processes were undertaken. Griesbach [4] was investigating the material flow under the blank holder in order to control the process. Also Bräunlich [5] and Yun [6] used the draw-in to control the process. These works used the curve shapes of the draw-in during the process rather than the final value after forming. First tests of systems, which use not only the draw-in but also material data and other parameters were done by Neumann [7].

## 2. The Q-Guard approach

The aim of the Q-Guard system is not only to set up a process control, but also to link product and process design to production. This way a-priori knowledge from process design and numeric simulations can be used to set up the process control. Stochastic simulations of the process are used to generate metamodels that describe the process behavior and can be used in the control system.

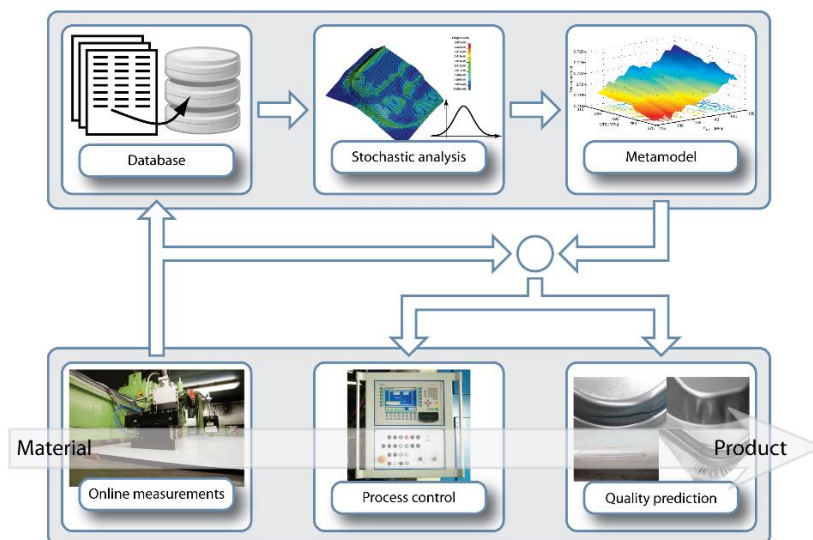


Figure 1: idea of the Q-Guard system

In the production line, all relevant parameters from the raw material to the finished part are measured in-line. Material properties, sheet thickness, lubrication, process settings (blank holder forces, drawing velocity ...) and tool temperature are acquired and used in a feed-forward control. The draw-in is measured after the first draw and used for a feedback loop. In the feed-forward control, the metamodels are directly evaluated using optimization algorithms. This is also possible in the feedback loop, as a second approach, the metamodels can be used for the design of the controller. In order to have a complete retraceability, all blanks are marked with a unique identification number in a datamatrix code after cutting, using an inkjet printer. After destacking in the press line, the code is scanned and all data read from a database. The blank holder forces of the drawing press are then adapted by the feed-forward control based on the measured data.

All acquired data are stored in a database (One part = one dataset) and available for the layout of future processes, in order to design processes based on real world data, or for follow-up checks of produced parts e.g. in case of complaints.

The process that is analyzed and controlled in this work is the deep drawing of kitchen sinks at Franke AG in Switzerland. These sinks are produced in a two-step deep drawing process, but only the first drawing step is controlled and thus closely investigated. The sinks made from stainless steel 1.4301 with a thickness of 0.8 mm, the material coming from different suppliers (Posco and AST).

### 3. Virtual Process

The underlying metamodel, based on numeric simulations, is crucial for the applicability of the Q-Guard approach. Hence several aspects must be treated carefully to achieve optimum accuracy of the virtual process. The material model has to be optimized, taking into account all possible effects of the material. Since the parts are made from metastable stainless steel, especially Martensite forming has to be considered. Friction behavior is based on strip drawing tests done at the institute and evaluated using the draw-in measured from a 3d scan of some manufactured parts. Numeric simulations are done in AutoForm using AutoForm Sigma. The metamodels are then generated using the AutoForm data. The metamodels are not only used for the process control, they are also evaluated regarding sensitivities of the process and process robustness.

#### 3.1. Material modelling

Since the Martensite volume of the material generated during deep drawing is crucial for the forming behaviour of the material, the full Hänsel model including temperature dependency was implemented (equation 3.1). In this model,  $A_{HS}$ ,  $B_{HS}$ ,  $m$ , and  $n$  are the standard parameters for a Hockett-Sherby approximation,  $\phi$  is the strain,  $K$  is a correction coefficient for the temperature,  $T$  is the temperature,  $T_{ref}$  is the reference temperature - in our case  $80^\circ\text{C}$ ,  $\Delta k_f^{\gamma \rightarrow \alpha'}$  is a coefficient to account for Martensite related hardening and  $V_m$  is the Martensite volume.

$$k_f^{total} = \left[ B_{HS} - (B_{HS} - A_{HS}) \cdot e^{-m \cdot \phi^n} \right] \cdot \left[ 1 - K \cdot (T - T_{ref}) \right] + \Delta k_f^{\gamma \rightarrow \alpha'} \cdot V_M \quad 3.1$$

In order to achieve optimal simulation results, separate material models for both material suppliers were generated. The results for AST and Posco material are shown in Figure 2 and Figure 3. The base yield curve for each material was measured at  $80^\circ\text{C}$ , where no Martensite is formed. There is a clearly visible difference in the yield curves for the two materials. The Posco material reaches much higher stresses, although both materials start at the same yield stress.

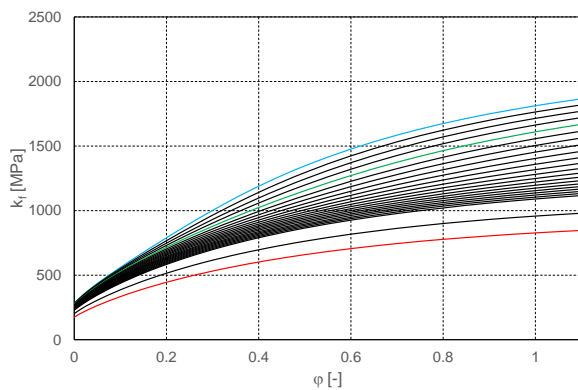


Figure 2: yield curves for AST steel (blue:  $0^\circ\text{C}$ , green:  $20^\circ\text{C}$ , red:  $200^\circ\text{C}$ )

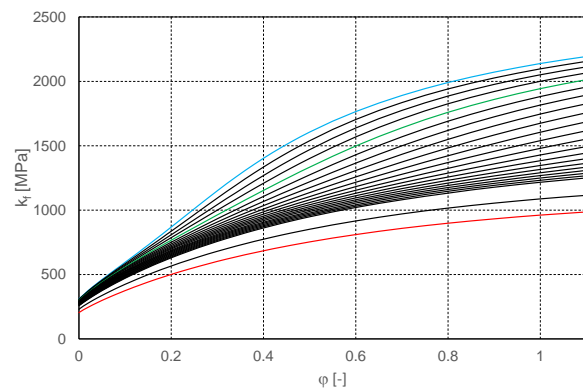


Figure 3: yield curves for Posco steel (blue:  $0^\circ\text{C}$ , green:  $20^\circ\text{C}$ , red:  $200^\circ\text{C}$ )

Another difference between the two materials is in the r-values. The  $45^\circ$  r-value for AST is 1.18, for Posco it is 1.33. These results depict one big problem in the process design for stainless steels. Since even materials with the same specifications can differ considerably, problems in production will occur, because the process design is optimized based on one specific material model. Very often the process windows are not large enough to tolerate such scatter of the material properties.

#### 3.2. Friction modelling

One big influence on the accuracy of the numeric simulation is the tribology. In this work coulomb friction is used. The friction setting in the simulation is based on strip drawing tests at the institute. These

tests are done at different temperature levels. To account for the heating up of the tools in production. At room temperature a friction coefficient of  $\mu = 0.07$  was measured and used in the numeric simulation. The simulation results are validated with the 3d scanned geometries of real parts. The draw-in contour of the simulated part is compared to the corresponding real part. These contours matched very well, indicating a correct friction coefficient was used in the simulations. In the AutoForm Sigma simulations  $\mu$  was varied from 0.05 to 0.12.

### 3.3. Numeric simulations

The material model and the friction data are used to set up the nominal simulation of the part. To get an idea how the part behaves, several quality criteria are checked (thinning, wrinkling, max. failure, etc.). It has to be noted, that in this project we are only considering the first deep-drawing operation. Therefore we are looking to have an optimal first step to ensure good parts after the second draw.

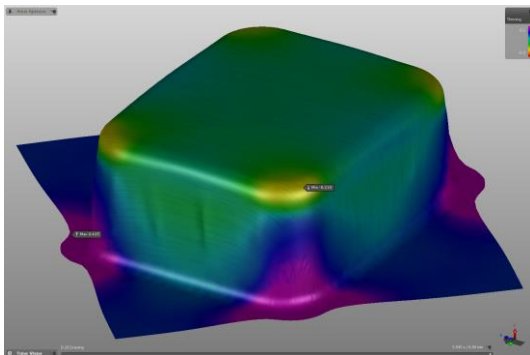


Figure 4: nominal simulation - thinning

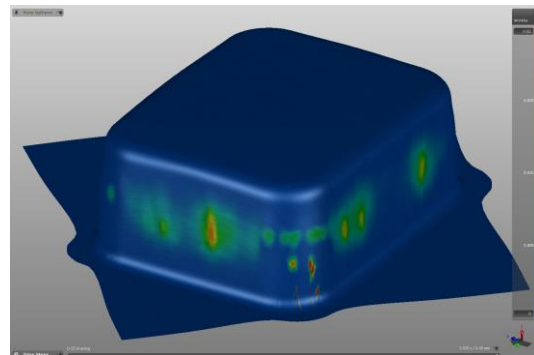


Figure 5: nominal simulation - wrinkling

In Figure 4 thinning is shown, which is not a very critical criterion, as long as the stretching in the bottom of the sink is sufficient. With a minimum of 6% stretching, this is reached everywhere. The wrinkling in Figure 5 seems to be critical, but all wrinkles can be removed in the second step.

Using the nominal simulation, an AutoForm Sigma run is done. Seven parameters are varied (Table 1), where the tensile strength is defined as depending from the yield strength. In Sigma, 100 simulations are done to generate data for the required metamodelling reproducing the process behaviour.

**Table 1.** Variation parameters for the AutoForm Sigma run.

Parameter	Minimum	Maximum
<b>Total press force until 70 mm</b>	2 000 kN	4 200 kN
<b>Total press force from 90 mm</b>	1 500 kN	3 000 kN
<b>Friction coefficient</b>	0.05	0.12
<b>Blank position (y-direction)</b>	-15 mm	+15 mm
<b>Yield strength</b>	239 MPa	289 MPa
Tensile strength (dep. from yield strength)	710 MPa	810 MPa
<b>Mean r-values (+/- 10 %)</b>	0.975	1.192

### 3.4. Metamodeling

For each selected quality criterion a separate metamodel is calculated. These quality criteria are

- Max. failure in the bottom corners
- Thinning in the bottom corners
- Potential wrinkling in the side walls
- Shear in the inlet corners

Using these metamodelling, correlation maps are calculated to visualize the process behaviour and to show correlations between the draw-in and the selected quality criteria. This way, the locations where the draw-in has to be acquired in-line are chosen. Figure 6 shows the correlation maps of two quality

criteria, thinning in the top right corner of the bottom and wrinkling in the sidewall at the spout. These diagrams show a clear correlation of the two quality criteria to the corners of the deep drawn part. Green stands for a correlation of 1, red means 0. For the correlation maps positive or negative correlations do not make a difference. Interestingly, the wrinkling at the sidewall is not so much influenced by the draw-in at the adjacent corner, but by the three other corners.

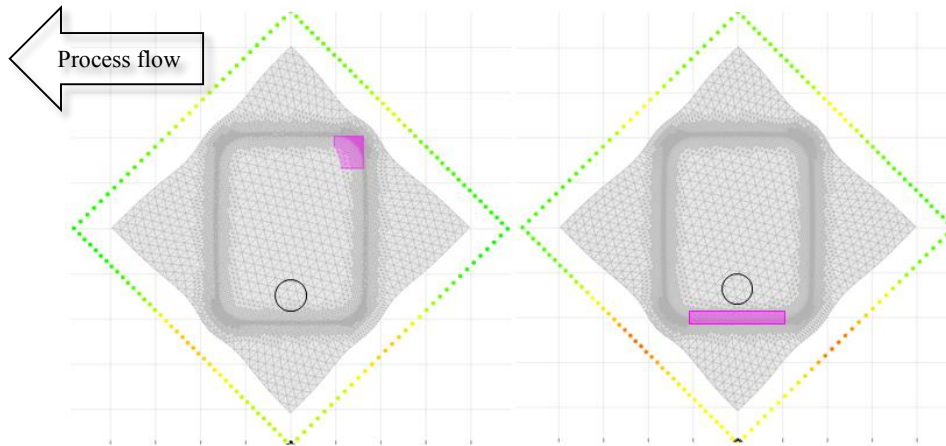


Figure 6: correlation of draw-in to selected quality criteria (in the pink areas); left: thinning, right: potential wrinkling

A detailed sensitivity analysis to understand process behaviour is done using graphs as shown in Figure 7. Such diagrams are plotted for all process parameters and quality criteria. The bar color in the graph shows the level of correlation (Table 2). In these diagrams, the correlation/sensitivity can also be negative.

**Table 2.** Correlation levels in the bar plots, the levels apply for positive and negative values.

Colour	Correlation	From	To
Red	insufficient	0	0.7
Orange	low	> 0.7	0.75
Yellow	good	> 0.75	0.8
Green	high	> 0.8	1

In Figure 7 the correlation of the thinning criterion in the top right corner is shown. This quality criterion has a very low correlation to the friction and the total press force (F<sub>tot-until100beforeBDC</sub> and F<sub>tot-from80beforeBDC</sub>). On the other side, it is highly correlated to some of the locations of the draw-in measurement (S1, S2, S4). In Figure 7, MF stands for MaxFailure, TH for thinning and PotWR for potential wrinkling at specific locations of the part.

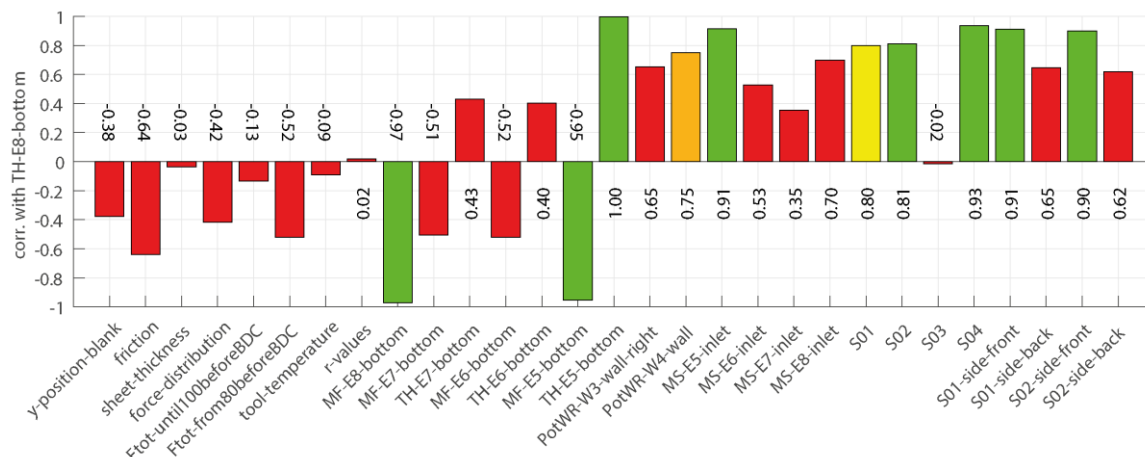


Figure 7: sensitivities of process parameters, quality criteria and draw-in positions to the thinning in one of the corners

By using these correlation diagrams the position of the draw-in measurement is selected and the behaviour of the control system is validated. More details of the metamodeling approach that is used in this project, can be found in the work of Harsch et al [8].

#### 4. Hardware

Several measurement systems are integrated into the production line (blanking and stamping) at Franke. The setup of the Q-Guard system is shown in Figure 8. In the blanking line the sheet thickness and the material data are acquired and each blank is marked. In the press line, the blanks are scanned and the corresponding data loaded into the process control. Additionally all process settings (lubrication, forces, velocity, etc.) are read into the process control. After the first deep drawing step, the optical draw-in measurement takes place.

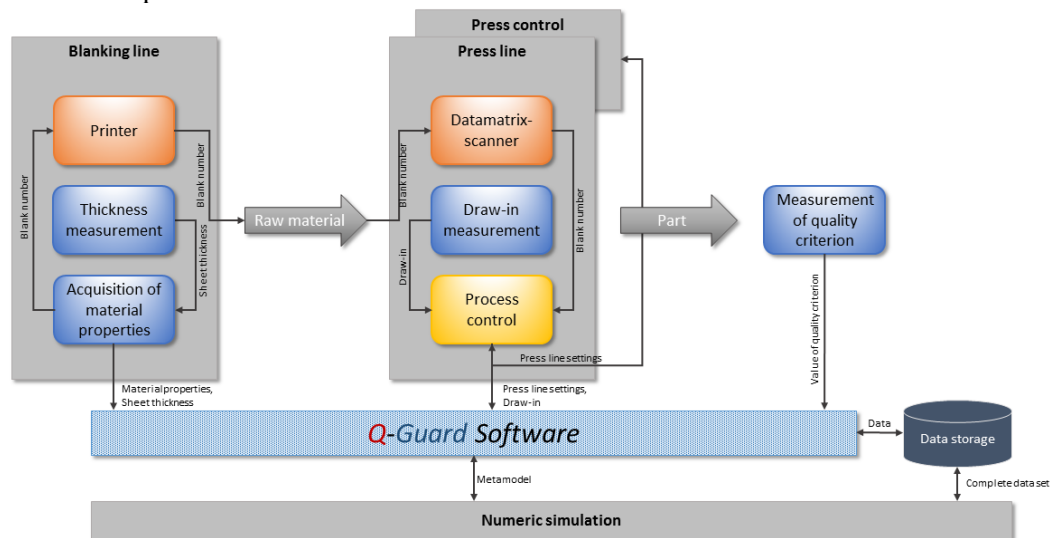


Figure 8: hardware setup of the Q-Guard system in the production line.

In the end, one region of finished part can be scanned (not entirely in-line though) using an optical measurement system. This way production can be linked to the simulation results. The modular Q-Guard software is the link between the blanking line, the press line, the database and the numeric simulations.

##### 4.1. Material data

In the blanking line, the measurement of material data takes place. To measure the sheet thickness, laser triangulation sensors are used, which are mounted on a c-shaped mounting. The material properties are acquired by eddy-current. The properties measured are the yield strength, tensile strength, uniform elongation, breaking elongation and the grain size. More information about the eddy-current measurement system integrated into the blanking line at Franke AG can be found in a paper from IDDRG2013 in Zurich [10].

##### 4.2. Draw-in Measurement

After the first draw, the part is re-lubricated on the inside. During this operation the optical draw-in measurement is done. While the robot holds the part on the lubrication station (Figure 9), an image from a camera mounted above the part is taken and evaluated. The measurement system itself consists of a camera (resolution 2750 x 2200 pixels) plus lens (focus length = 25 mm) and an illumination system, both of which are mounted on a frame made of aluminum profiles. The camera is connected to a computer through TCP/IP. It is triggered through the robot and in return triggers the illumination when taking a picture. To increase measuring accuracy the system uses four flashlights in a square shaped arrangement as an additional illumination to shorten exposure time. This way any movement of the part and/or the camera through vibrations is frozen resulting in sharper edges in the image. The focal plane



of the camera is at the flange of the part for the same reason. The measurement system works in a way that the deviation of a measured part's contour in relation to a reference part is calculated (Figure 10). Since the part is slightly moved by the robot arm when lifting it, the software has to calculate the distance and rotation of each part compared to the reference part. This deviation has to be compensated during image processing.

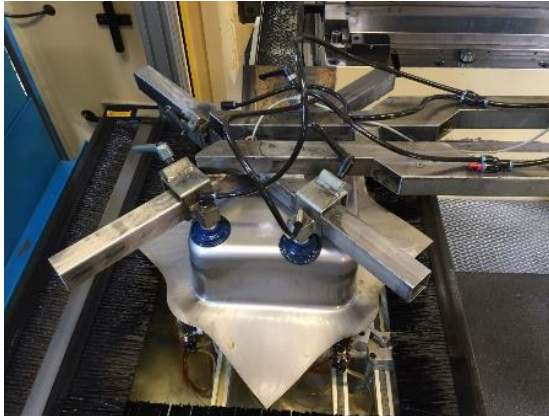


Figure 9: a part in the lubrication station

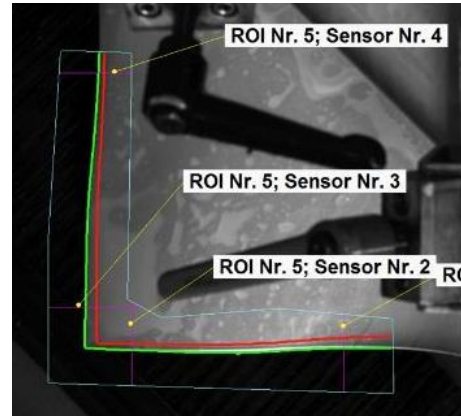


Figure 10: zoom in on the bottom left corner

The data acquisition software can either be integrated into the Q-Guard environment or used as a stand-alone program, according to the modular approach of the Q-Guard system.

#### 4.3. Marking and scanning

In the blanking line, each blank is marked with a unique identifier using a Hitachi inkjet printer. This allows for a complete retraceability of each blank. The identifier is printed on the blank as characters as well as a datamatrix code. In the database a complete dataset for each blank is stored. After the blanking line this dataset consists of the order number, material batch number from the supplier, the mechanical properties and the thickness. After destacking in the press line, a datamatrix scanner reads the blank identifier and accesses the data from the database. Together with the tool temperature, the lubrication and the press settings, these data are used for the feed forward control. After the part is manufactured, the new data including the draw-in results are added to the database.

### 5. Process Control

The layout of the process control is shown in Figure 11. The generated virtual knowledge from numeric simulations is used in both parts of the control system, the feed forward control and the feedback loop.

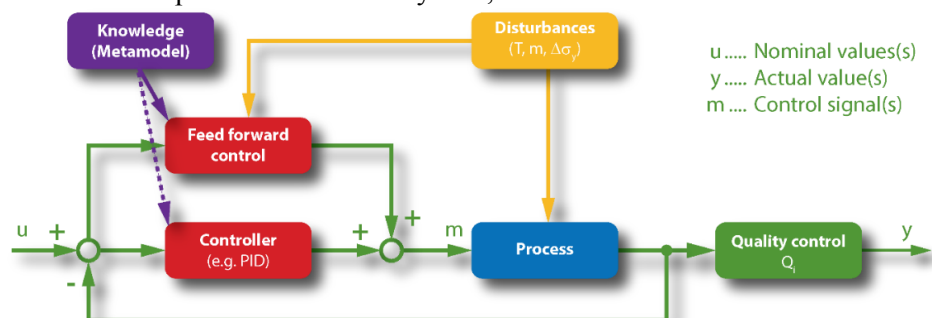


Figure 11: layout of the process control

In order to test the control system, first experiments were performed. Based on the machine settings for good parts, the settings were changed and the control system had to adapt the settings back to the optimum. In a first run, a simple PI-controller was used, that was designed using the metamodels from numeric simulations (Figure 12). In a second attempt a direct optimization of the metamodels was used

(Figure 13). Both algorithms worked well, especially the optimization algorithm found the optimum settings very fast, it was slightly overshooting though. After 4 parts, the controller reached a steady state.

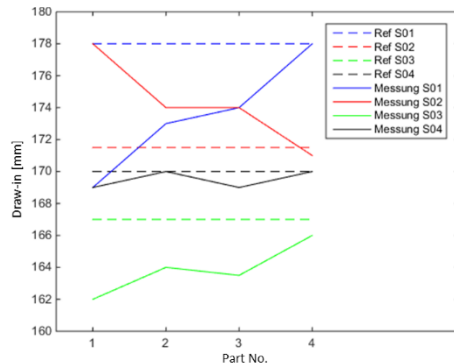


Figure 12: simple controller based on metamodel.

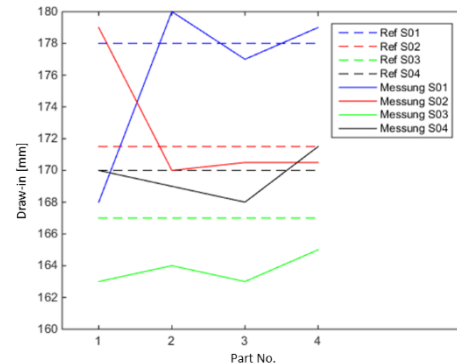


Figure 13: direct optimization of metamodel

## 6. Conclusions

The in-line acquisition of all relevant parameters works very well in production and a control system, capable of finding the optimum settings for the investigated process can be implemented based on numeric simulations and in-line measured data.

## Acknowledgements

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