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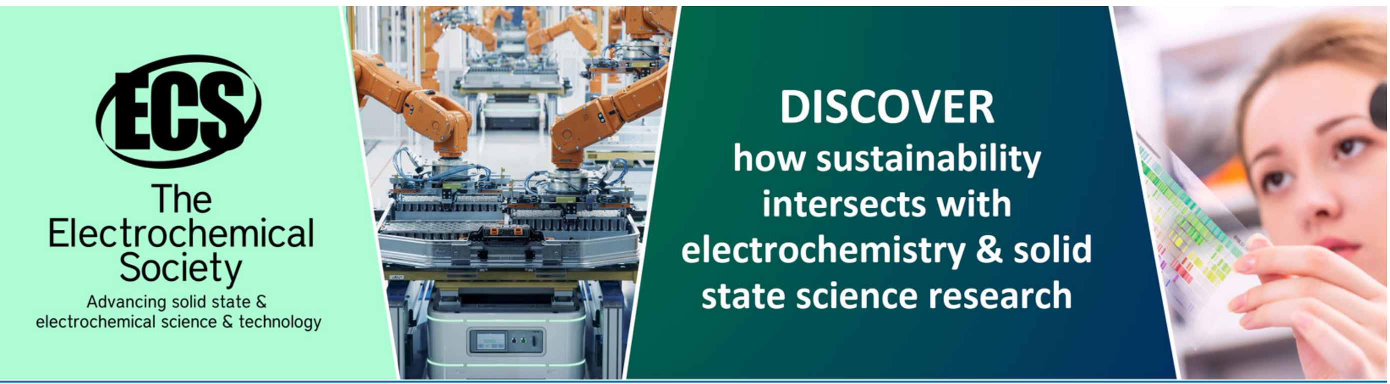

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Inline feedback control for deep drawing applications

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Abstract. In series production of deep drawing products the quality of the parts is significantly influenced by material scatter. To guarantee a robust manufacturing the processes are designed to have a large process window. As the different material properties can lead to a drift in the process, the press settings have to be adjusted to keep the quality. In the scope of the work a feedback control system is proposed to keep the operation point inside the process window. The blank draw-in measured in predefined points is used as the primary indicator of the expected part quality. A simulation based meta model is then used to design the control algorithm with the blank holder forces as control variable. As the draw-in measurements are carried out punctually, their positioning within the tool becomes of critical importance. A simulation based study is therefore presented for the identification of sensor positions with the highest significance in relation to the process outcome. The baseline calibration of the controller is also based on the meta model. The validation of the proposed control system is illustrated based on experiments in a production line.

1. Introduction

The robustness in series production of deep drawing parts is greatly influenced by tool design, as well as scattering material properties and process noise. In literature different approaches can be found to visualize the working windows [1] as well as to widen the windows [2], [3]. Due to the increasing complexity of deep drawing parts, the process windows cannot be kept as wide as wanted, therefore a different approach has to be added to keep the processes inside the narrow windows. To account directly for the changing material properties like yield strength or tensile strength, as well as to reduce the influence of the process noise, like changes in friction due to the heating of the tools, a closed loop feedback control has to be introduced. In order to achieve a robust control, the measured feedback value should be controllable by the possible actuators as well as it should be representative for the process noise which should be canceled out. To keep the investment costs as low as possible, no additional actuators should be introduced to the tool. Therefore the blank holders are chosen as actuators, as well as the blank position which can be easily adjusted in the production of the chosen demo part. As demo part, a kitchen sink made from 1.4301 stainless steels is chosen. In the following the different stages for the design of the control algorithm are show, beginning with the classical finite element analysis of the demo part, followed by building a meta model from stochastically distributed simulations. In the end the model is validated as well as the control approach is tested in the production line.

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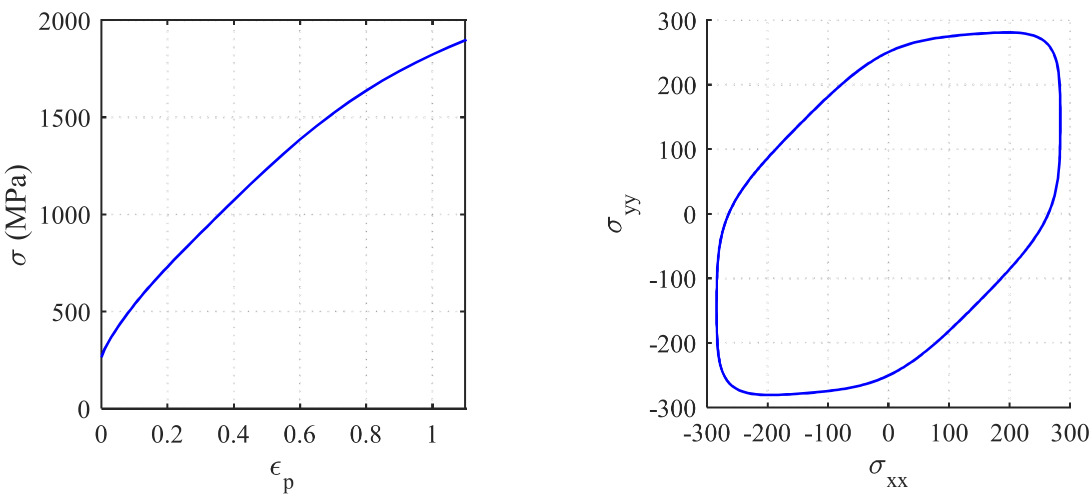
2. Modelling the process for virtual analysis

For the development of control approaches it is indispensable to generate a model for the purpose of testing and evaluation of different algorithms. As the demonstrator is already in series production, the first step in building up the model is the generation of a finite element model at the nominal working point. In the next step stochastically distributed simulations inside a defined multidimensional space (friction, forces, etc.) are evaluated and based on the evaluations, the control variables as well the as the sensor positions are chosen.

2.1. Nominal FE-model

The nominal simulation of the forming process is generated in agreement with the process settings in the series production. For a better approximation of the process, one charge of the material is thoroughly tested. As baseline material model for the stainless steel 1.4301, the Hänsel model [4] is chosen and therefore tensile tests at six different temperatures are carried out, as well as the bulge test. For purpose of fitting of the model, the martensite content and forming rate during the tensile test are measured as well. In order to reduce the calculation time as well as to suit the needs of the industry partner, the model was collapsed to a single yield curve at 30 degree Celsius (figure 1a) for the calculation of the forming process in AutoForm. As model for the yield surface (figure 1b), the BBC 2005 implementation in AutoForm[5] was chosen. Compared with the other available yield surfaces, the BBC model has the highest flexibility and can therefore be fitted best to the extensive test data. The BBC yield surface is fitted to the three Lankford coefficients (0.861, 1.333, 0.807), the biaxial R-value of one, as well as the as the yield stresses σ_0=264 MPa, σ_{45}=247.7 MPa, σ_{90}=250.6 MPa and the biaxial yield stress σ_b=262.9 MPa



(a) (b)

Figure 1. Yield curve(a) and Yield locus (b)

As opposed to the try-out phase in automotive industries, the tools in the kitchen sink production are usually not modified and therefore the nominal milling geometry can be used for the simulation, instead of digitalized tool. With the experience of the series production a force curve for the blank holder force is chosen, which shows a decreasing ramp of the force between a drawing depth of 80 mm and 100 mm, while the overall drawing depth for the given part is 180 mm. Therefore a force of 2000 kN until 80mm and a force of 750kN from 100 mm on is chosen. The simulation shows acceptable agreement in thinning and is therefore chosen as the basic model for the upcoming variant simulation.

2.2. Meta model for draw-in

For the generation of an accurate model, the process has to be varied in a wide area to cover all possible process windows. A special focus in variation has to be laid on the possible actuators for the process control, therefore the two different force settings are varied independently to have the option of shifting them correlated or of changing them independently in the control algorithm. The forces are varied asymmetric to their nominal value, as the experience shows that shifting the forces to a higher level as the 2500 kN can lead to base fractures in the process as well as in the simulation, which have to be rejected as outliers in the meta model. The shift in the column position might be another possibility of controlling the symmetry of the draw-in and is therefore varied as well. As the positioning of the blank is one of the control parameters in manual press adjustment, the variation for the model is specified a bit wider than it usually occurs in the manual search for a robust process. The last three variation parameters cannot be directly influenced by the operator and therefore considered as process noise. For the calculation in AutoForm, the yield stress is directly coupled with yield strength and the variation band is based on pilot tests of the eddy-current measurement for stainless steel [6], while the variation of the Lankford coefficients is chosen to be between plus and minus ten percent of the values determined in the tensile tests. As the friction in the process is greatly influenced by the tool temperature and the amount of lubrication which is left in the tool, the friction coefficient is varied over an extremely wide band to map all possible states of the tool. The finally chosen variation values can be seen in table 1.

Table 1. Input variations for meta model

Parameter	Lower limit	Nominal value	Upper limit
Force until 80 mm	1000 kN	2000 kN	2500 kN
Force after 100 mm	400 kN	750 kN	1000 kN
Column position x-direction	-50 mm	0	50 mm
Blank position x-direction	-20 mm	5 mm	30 mm
Coulomb friction μ	0.05	0.07	0.15
Yield stress / yield strength delta	-25 MPa	0	25 MPa
R_0	0.7749	0.861	0.9471

The next step after choosing the variation variables and the variation range, is setting up an appropriate design of experiments. As the influences of the different parameters might be highly nonlinear, a latin hypercube design is chosen instead of a factorial design. Compared with the Monte Carlo design, the latin hypercube design has the advantage of iterating the design under certain boundary conditions to optimize the result. For the variant simulation with 90 simulations, the design was optimized under the condition of maximizing the minimal distance between the experiments and as second condition a limitation of the correlation between the different parameter is introduced.

The evaluation of the final correlation between the parameters shows that the Pearson correlation coefficient calculated for the design of experiments results in a maximal value of 0.14. As the correlation between the parameters is low, the results should not show any correlation which is introduced through the design of experiments. The draw-in at certain sensor positions, as displayed in figure 2, is evaluated and the correlation coefficient between draw-in and parameter is calculated.

The evaluation of the coefficients in table 2 shows that the possible actuators have acceptable correlation with certain sensor positions. The change in the blank holder forces can be recognized in the draw-in at sensor S03 and sensor S04, while the change of the blank position can be detected in all other sensors. As sensor S03 and sensor S04 show a good agreement with the friction coefficient, the measurement at these positions can be used together with the blank holder force to account for a change in friction. The change in the material is difficult to detect through the sensors, but the evaluation of different criteria like the maximum failure criteria shows, that a change in material does not significantly influence the process in the simulation. After choosing the sensor positions, it is necessary to build an

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appropriate model of the sensor input relation to generate a virtual testing environment for the control algorithms.

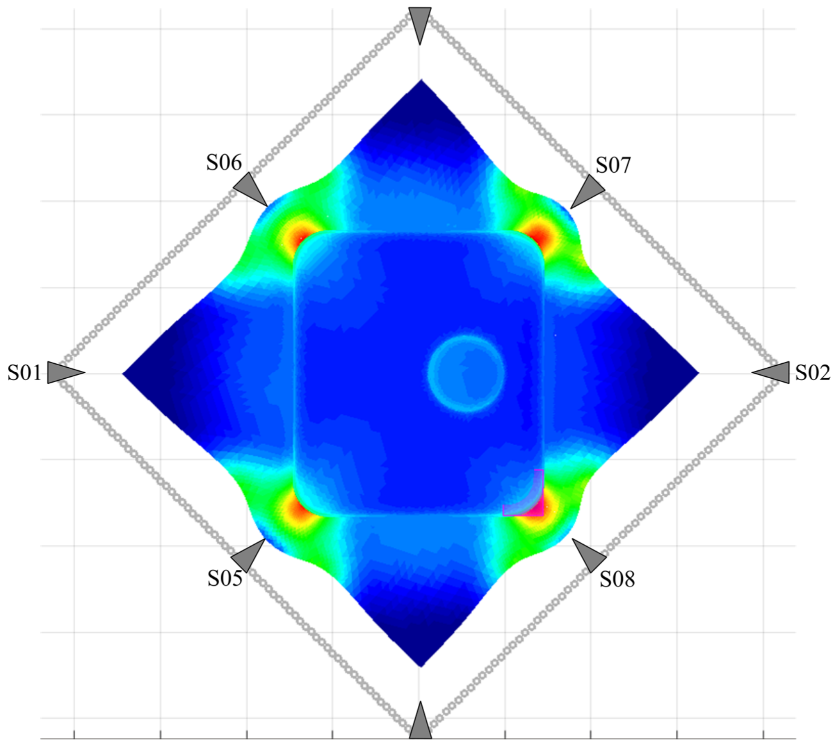


Figure 2. Position of virtual draw-in sensors

In general two different modelling approaches for the meta models can be used, the first approach uses approximating models, like response surfaces, while the second approach is based on interpolating models, like Kriging [2]. The usability of the different models is checked by cross validation. As the model is directly evaluated in the testing environment and not used in the controller, the complexity of the model can be neglected and model can be chosen based on the best fit. Therefore Kriging is used for sensor S01, while radial basis functions are used for sensor S02 and S03. Sensor S04 on the other hand showed the best result with the much simpler approximation by a quadratic function with interactions. In the evaluation of the correlations and the fitting of the functions, the inputs are normalized to reduce the influence of the different scales of the parameters. The knowledge about the current state of the part cannot be extended by the usage of sensor S05 to S08 and therefore the sensors are not used for the control.

Table 2. Correlation between results and variation parameters

	S01	S02	S03	S04	S05	S06	S07	S08
Force until 80 mm	0.031	-0.211	-0.226	-0.223	0.071	0.075	-0.216	-0.213
Force after 100 mm	-0.065	-0.187	-0.410	-0.405	0.068	0.064	-0.121	-0.123
Column position x-direction	0.421	-0.324	0.185	0.203	0.274	0.275	-0.170	-0.170
Blank position x-direction	0.813	-0.827	-0.074	-0.054	0.904	0.905	-0.883	-0.884
Coulomb friction μ	-0.295	-0.300	-0.844	-0.845	-0.216	-0.214	-0.266	-0.264
Yield stress / yield strength	0.038	0.075	-0.114	-0.113	-0.120	-0.124	-0.101	-0.103
Lankford coefficients	0.072	-0.065	0.047	0.056	0.049	0.049	-0.074	-0.071

Based on these models, the virtual testing environment can be designed.

3. Design of control model and definition of control parameters

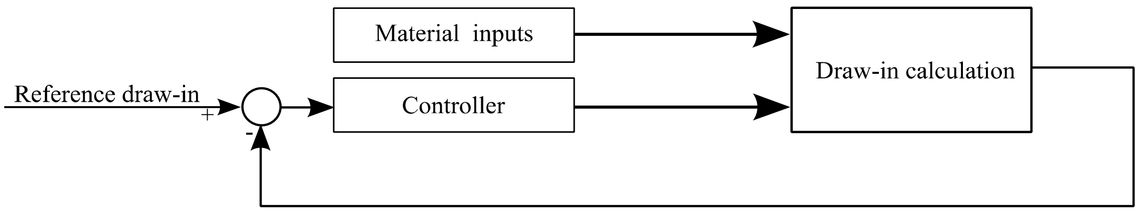


Figure 3. Scheme of the virtual test environment

The virtual try-out system for different control approaches is built up in MATLAB Simulink and consists of the three sub-systems shown in figure 3. In the material inputs section the process noise like material and friction can varied in the range of the meta model, while the actuating parameters are set and calculated in the controller section. Finally the values of both sections are taken for the calculation of the current draw-in which is fed back to the controller as deviation from the reference part.

The independency between the response of the sensors S01, S02 and S03, S04 results in a decoupled MIMO system. As the sensors S01 and S02, respectively S03 and S04, contribute to the same actuator, their deviations can be combined by simple arithmetic to a single control input. These simplifications lead to two independent SISO systems. The most common control algorithm for SISO systems, is the PID-controller. As the part to part variation in friction and material properties is low, the PID-controller has no need to react extremely fast and accurate, therefore it can be simplified to a proportional controller. The second reason for the application of a proportional controller is the low curvature of the models which reduces the risk of getting wind up in a local minima of the process, as the P-controller is similar to the Newton optimisation method which would not be able to find the global minimum in a function with local minima.

For finding the controller gains, different parameter settings have been tested. A high gain leads to a faster response of the controller, but can lead to overshoots, while a small gain reduces the risk of overshoots, but on the other hand it might be too slow to influence the process significantly. The chosen parameter settings aim to reach the reference draw-in within five to ten parts, while the overshoot should be marginal. Finally a shift of 0.4mm in blank position per mm of the combined deviation in the draw-in of the sensors S01 and S02 is chosen. The correction factor for the blank holder force is chosen to be 60kN per mm of the combined deviation of sensor S03 and S04. With the definition of the controller gains, the requirements for testing the process control are fulfilled.

4. Experimental set-up

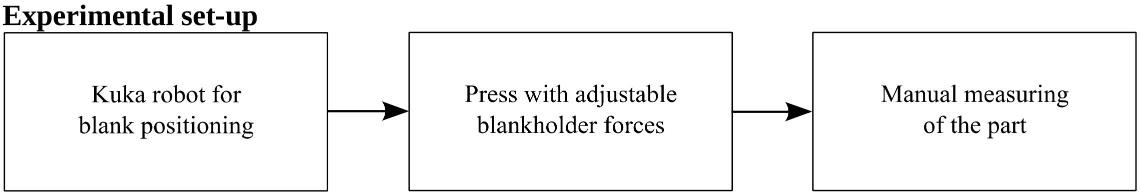


Figure 4. Scheme of experimental set-up

In the series production line, the implementation of the control would require direct control of the first two blocks in the scheme shown in figure 4 and is therefore highly complex. For that reason the settings calculated by the control algorithm are transferred by an operator for the purpose of testing the system. As the draw-in is nearly impossible to measure in the deep drawn part, the remaining flange is measured instead and then converted for the controller. As the measurements are done manually the repeatability and also the accuracy lies within the error of 1mm. The set-up is chosen to demonstrate the functionality of the control algorithm without the need of the complex integration.

5. Results

5.1. Correlation in experiments

Before the control can be tested it is necessary to determine if the calculated meta model corresponds to the real process behaviour. Therefore a design of experiment is carried out, where the blank holder force and the blank position are set to the values shown in figure 5. The shown force is the force until 80mm, while the force at 100 mm is the force of 80 mm divided by 2.66. The factor 2.66 is based on the experience of the press operators. The experimental design of experiments leaves the virtual design space, due to the fact that a scaling factor is introduced after the first comparison of the simulation with an experiment. The correlation between the chosen sensor and the corresponding actuators lies around 0.98 for the blank position and around 0.92 for the blank holder force. This leads to the conclusion that the draw-in at the sensor position is controllable with the chosen actuators. The results of these nine parts compared with the expected draw-in, shows that the influence of the blank position is approximated quite well, while the overall model seems to have a small offset even with the previous introduced scaling. The influence of the blank holder forces on the over hand looks underestimated. All in all the trends are predicted well enough and therefore the tests with the control algorithm can be carried out.

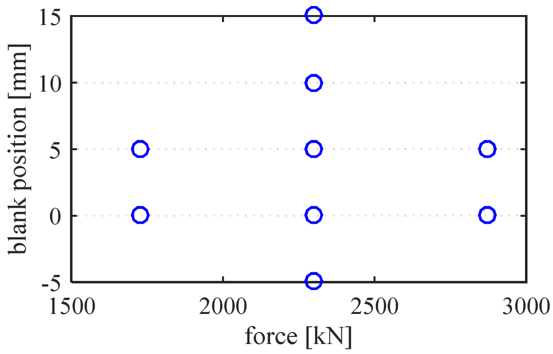
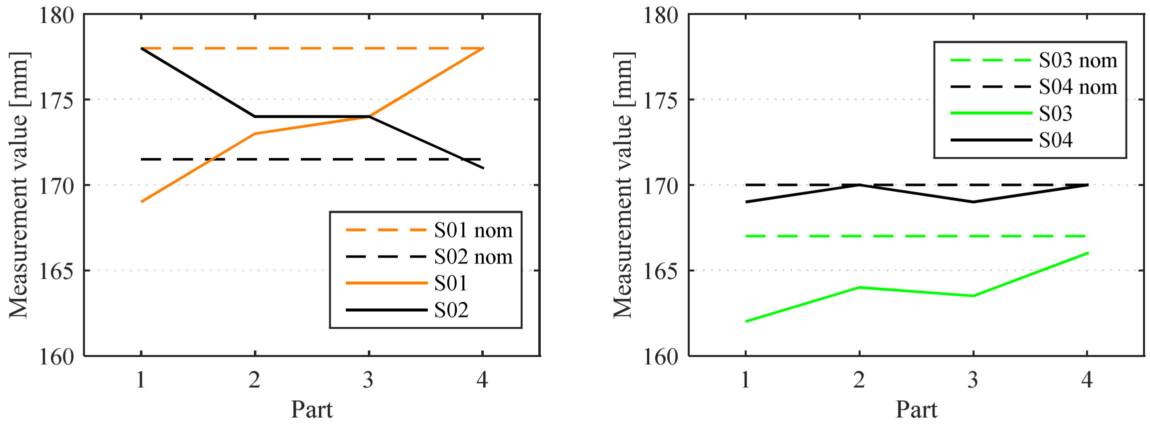


Figure 5. Input scatter of experimental try-out

5.2. Feedback control

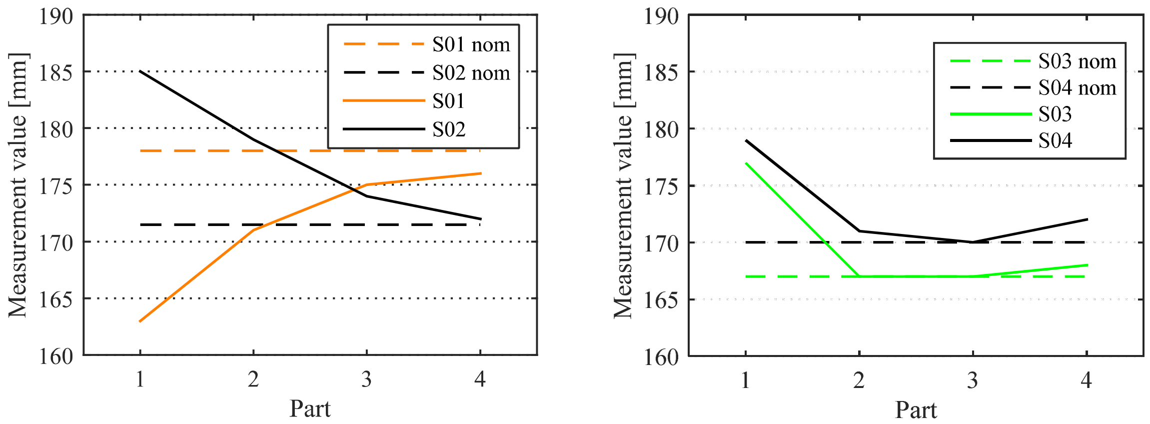
With the boundary condition of using the series production line the decision is taken to use four parts per run. As no change in material is possible in such a small number of runs, the decision is taken to prove the concept by starting from a random point in the design space with the aim of finding back to the reference settings.

The reference settings are 2300kN and a shift in the blank position of 0mm from the center. These results in the measured remaining flange which can be seen as S01-S04 nom in figure 6 and figure 7. For the first controlled run a starting position with a too low force of 1725kN and a positive shift in the blank position of 5 mm is chosen. The graph in figure 6a shows the influence in the shift of the blank, which is taken back by the control algorithm until the nominal value is reached at part four. In figure 6b the influence of the adaption of the blank hold forces can be seen, also it is clearly visible that the part is already missing the symmetry in the reference value and therefore reacts differently than it would be expected. All in all at part four the nominal geometry is reached inside the measurement error.



(a) (b)

Figure 6. Results of the first run with feedback control



(a) (b)

Figure 7. Results of the second run with feedback control

For further validation of the control algorithm, a second run from a different starting point is carried out. The second starting point with a force of 2875 kN and a shift in the blank position of 10 mm lies further away than the one in first run. In figure 7b it can be determined that the blank holder force correlated sensor values reach their nominal value even quicker that in the first run, but diverge insignificantly at part 4, as the divergence is still close to the measurement error. The blank position related values in figure 7a on the other need longer to reach their nominal values as the distance to the reference value is larger. In sensor S01, the changing slopes can be explained directly by the proportional controller which reduces the change proportional to the distances between nominal value and current value. The same behaviour might not be visible in the other figure due to some side effects of friction or the combined change of both parameters. All in all the controller reaches again the reference point.

6. Conclusion

The results clearly show that the controller is able to improve the performance in the production of kitchen sinks. It also shows that developing a control algorithm based on a solid meta model reduces the calibration time for the controller as the shown results are the first experiments carried out with the controller. The defined meta model can not only be used for the design of the controller but also used generally in the search for a working point and therefore the extended computation time is used wisely.

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The next step in the development of the feedback control is the integration into the production line as industry 4.0 application.

References

[1] C. Annen, “Entwicklung einer neuen Methode zur Ermittlung und Visualisierung von robusten Prozessfenstern in der Blechumformung,” Zürich : ETH, Zürich, 2012.
[2] M. H. A. Bonte, “Optimisation strategies for metal forming processes,” Enschede, 2007.
[3] J. H. Wiebenga, “Robust design and optimization of forming processes,” Enschede, 2014.
[4] M. Hans Christian Andreas Hänsel Deutschland, 1969 -, “Nichtisothermes Werkstoffmodell für die FE-Simulation von Blechumformprozessen mit metastabilen austenitischen CrNi-Stählen,” Düsseldorf : VDI Verlag, Düsseldorf, 1998.
[5] D. Banabic, D. S. Comsa, M. Sester, M. Selig, W. Kubli, K. Mattiasson, and M. Sigvant, “Influence of constitutive equations on the accuracy of prediction in sheet metal forming simulation,” in *7th International Conference NUMISHEET*, 2008.
[6] J. Heingärtner, Y. Renkci, and P. Hora, “Non-destructive testing of material properties,” in *6th Forming Technology Forum*, 2013.