Implementation of a tribology-based process control system for deep drawing processes

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Abstract. Modern deep drawn parts have complex designs and are driven to the limits of the material formability in order to reduce costs. This leads to small process windows and unstable forming processes with high scrap rates. Especially at the beginning of a batch, when the tools are warming up, high scrap rates can occur due to the changing friction behaviour of the system tool – lubricant – metal sheet. To make processes independent from user experience and know-how, process control systems that can compensate for the transient behaviour of the process are desired. In this work, a process control system that is based on the numerical simulation of the friction behaviour of the deep drawing process is presented. The system makes use of numerical simulations of the transient behaviour during warming up of the tools. These simulations are used to generate metamodels of the process, which are used to design and optimize the control algorithm. The control system is tested with an automotive part from Opel. The control system itself consists of two parts: a feed forward controller and a feedback loop. In the feedforward loop the in-line acquired temperature will be used as an indicator for the friction conditions. It will make use of metamodels generated based on numerical simulations in order to depict the process behaviour. The feedback loop will use the in-line measured draw-in as a state variable in order to account for all other process influences. Simulation results, the generation of metamodels, as well as the first off-line tests of the process control are shown in this contribution.

1. Introduction

The complex part geometries of modern automotive parts result in deep drawing processes that are extremely sensitive to changing process parameters [1]. Especially the transient behavior of the tools during the warm-up phase after production start causes problems due to the influence of the tool temperature on the friction conditions and the material behavior [2]. Nowadays, the machine operators react to this behavior based on their experience – or if a part fails. By using a system that is capable of controlling the process and keeping it inside the process window scrap reduction and downtime of the press line can be reduced significantly [3]. The approach to implement such a system is to use knowledge that is generated from numerical simulations of the forming process to develop the process control and test it in a virtual environment before it is implemented in production [4] [5] [6].

At first, the baseline simulation is set up, which is used for the subsequent variant simulations of the part. In these simulations, the binder forces, the friction/tool temperature and other parameters are varied in order to account for the transient tool behavior. The results of the variant simulations are used to

generate metamodels of the forming process. These metamodels are evaluated to assess the process window, to check the observability of the selected quality features and to virtually test a possible control system.

2. Control system

The control system consists of two different controllers (Figure 1). Both of them make use of the metamodels calculated from numerical variant simulations. An open loop (feed forward) controller is used to adjust the process to the instantaneous friction conditions caused by temperature changes compared to temperature at production start. For the open loop controller the generated metamodels of the forming process are used and directly evaluated through an optimization algorithm. The closed loop (feedback) control uses the in-line measured draw-in of the finished part. This is done by calculating the deviation between the actual part and a reference part. It compensates all other influences that are not directly measured, like variable material properties or the blank position. The closed loop control uses a PI-controller that is designed by using the metamodels as a process model.
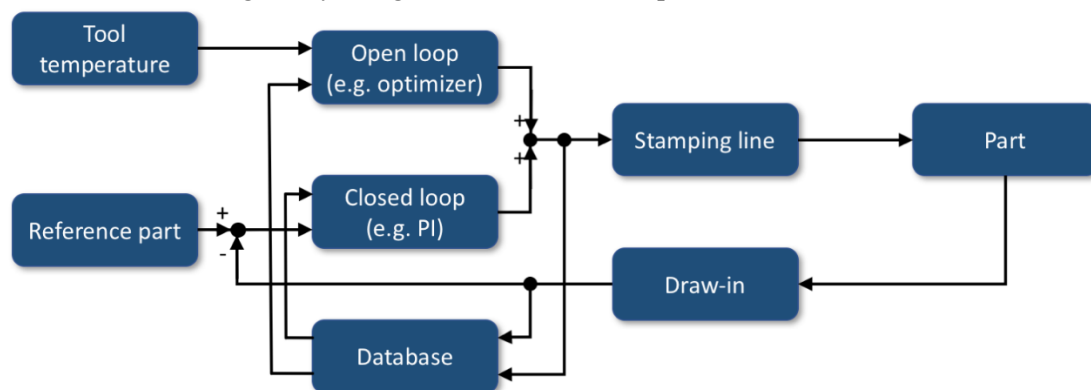
Figure 1. Setup of the control system.

The database in Figure 1 is not used in the current control system. In a second step, it will allow to build an adaptive control system that is capable to account for large changes of the friction conditions, e.g. if the lubrication amount is changed. In such a case the control parameters will have to change based on the measured temperature and the draw-in. These control parameters are stored in the database.

3. Numerical simulations

The part that is used for this project is a spare wheel well made from a hot dipped galvanized bake hardenable steel (GMW3032M-STS CR 180B2) with a thickness of 0.65 mm (Figure 2).


Figure 2. Spare wheel well of the Opel Insignia.

It is a symmetric part which is why in order to minimize simulation time, only one half is used in the simulations in this work.

This part is very sensitive to changing friction conditions. After approximately 500 parts of a batch, tool temperature is increased leading to a higher friction coefficient and the part starts to show a tendency to fail due to cracks.

The commercial finite element software, PAM STAMP, was used for simulations in this study. To generate the baseline simulation, the standard parameters delivered by Opel with the corresponding material parameters are used. The material model has a $\sigma_{p0.2}$ of 200 MPa and a UTS of 321 MPa. It uses a Swift yield curve approximation and a Hill48 yield locus with R-values of 1.6. The reason for the use of the standard model is the fact that it should be possible to implement a control system in the press-shop using the approach in this study. Therefore only data that are used for process design at Opel by default were used and no specialized material models are developed for this project. The baseline simulation is validated using a 3d scan with a GOM Atos system. The scanned geometry is shown in Figure 3. The green part is the scanned geometry, the green line is the draw-in from the numerical simulation. The scanned part was manufactured using a binder force of 1800 kN with warm tools.
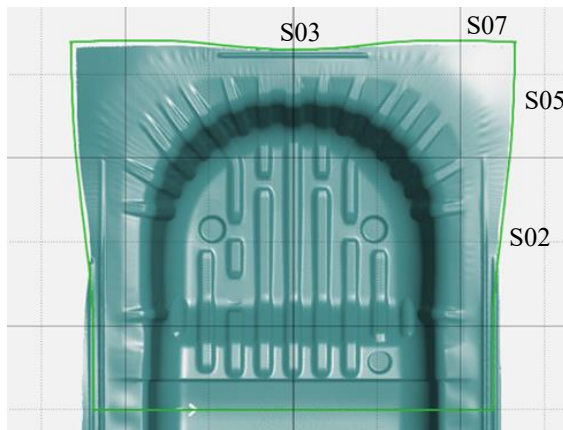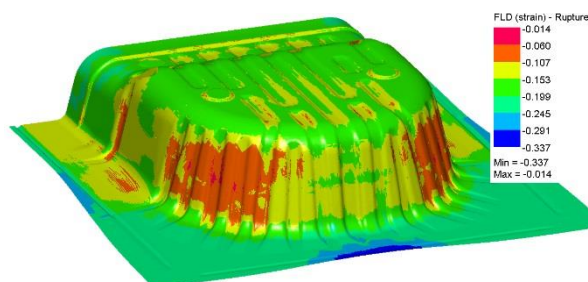

Figure 3. Failure criterion rupture risk.

**Table 1.** Draw-in of the real part and the simulation.

Sensor	Draw-in		Difference
	3d scan	Sim.	
2	93	90	3
3	78	78	0
5	63	56	7
7	69	55	14

Thinning and the draw-in contour are the parameters used for the validation of the material model and the friction coefficient used.

For the generation of the metamodels, the failure criteria *rupture risk* and *thinning* are taken into consideration. As can be seen in Figure 4 and Figure 5, the ribs on the left and the right side of the radius are critical for these two criteria. This behaviour is also observed on real production parts.

Figure 4. Failure criterion rupture risk.
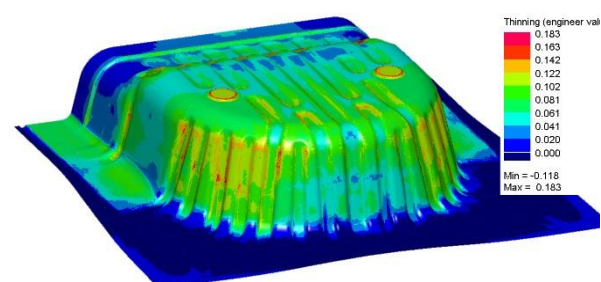
Figure 5. Failure criterion thinning.
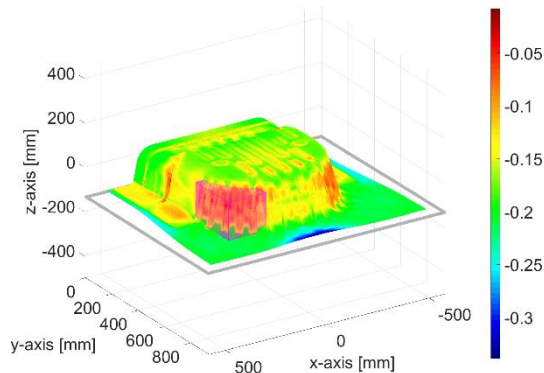
4. Metamodels

To calculate metamodels that depict the behaviour of the process correctly and cover the whole range of parameters occurring in production, variant simulations have to be calculated. The design of experiments and the whole evaluation of the results of these simulations are done in a tool called *Simuplan*, developed at the IVP and inspire. Using this tool a complete analysis of a deep drawing

process can be performed. Based on a design of experiments using a latin hypercube sampling, variant simulations are calculated, quality criteria to calculate metamodels are selected by the user and the necessary metamodels are generated. These metamodels are then used to assess process robustness, as well as observability and controllability of the selected quality criteria. A virtual test bench to perform a first virtual test of the control system is also integrated in the tool. The parameters that are adapted in the variant simulations and their range are shown in Table 2. These parameters are the input data (features) for the metamdodel. The quality criteria are the target values.

Table 2. Parameters and their range for the variant simulations.

| Parameter	Nominal value	Variation range
Binderforce	750 kN	400 - 800 kN
Friction coefficient	0.08	0.05 – 0.09
Sheet thickness	0.65 mm	0.62 -0.68 mm
Blank x-position	0 mm	+/- 2 mm
Blank y-position	0 mm	+/- 2 mm
σ_{p02}	200 MPa	180 – 230 Mpa
UTS	321 MPa	300 – 360 Mpa
R − values	1.6	+/- 10%

As can be seen in Table 2, not only the binder force and the friction coefficient are varied, but also the material properties and the blank position.
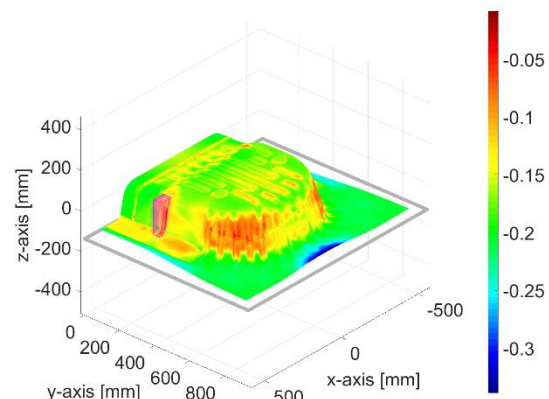

Figure 6. Rupture risk 01.
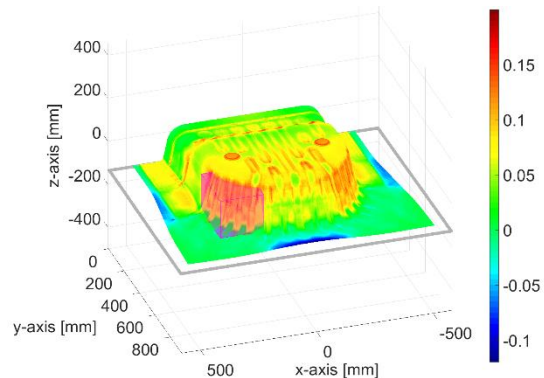
Figure 7. Thinning 01.
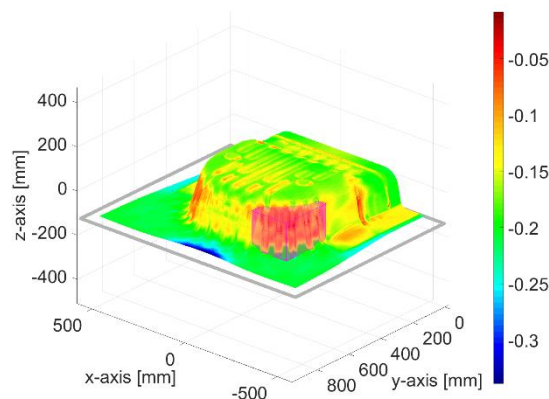
**Figure 8.** Rupture risk 02.

Figure 9: Rupture risk 04.

These parameters are used for the first sensitivity analysis and to calculate the process windows for good parts. To calculate the metamodels the relevant failure criteria are evaluated for specified regions

of the part. For each combination of region and failure criterion a separate metamodel is calculated. The different regions and the selected failure criteria are shown in Figure 6 - Figure 9 (the selected region of interest is marked in red). These are called quality criteria, because the results of the failure criteria in these regions mainly determine the part quality. The names of the quality criteria consist of the selected failure criterion (rupture risk or thinning) and the specific region, where the failure criterion is evaluated $(1 - 4)$. At the beginning, in the first step, more than these 4 quality criteria were investigated, but it turned out that some criteria are redundant, so they were skipped. Rupture risk is a failure criterion that predicts cracks in the part based on the forming limit diagram and is critical if it is above -0.04, thinning is the thickness reduction through the forming operation compared to the initial blank thickness, it is critical above 0.15.

The positions for the draw-in sensors were also evaluated through the calculated metamodels. The correlation of the draw-in calculated in all variant simulations to the selected quality criterion and the variation of the draw-in for the respective criterion are calculated.
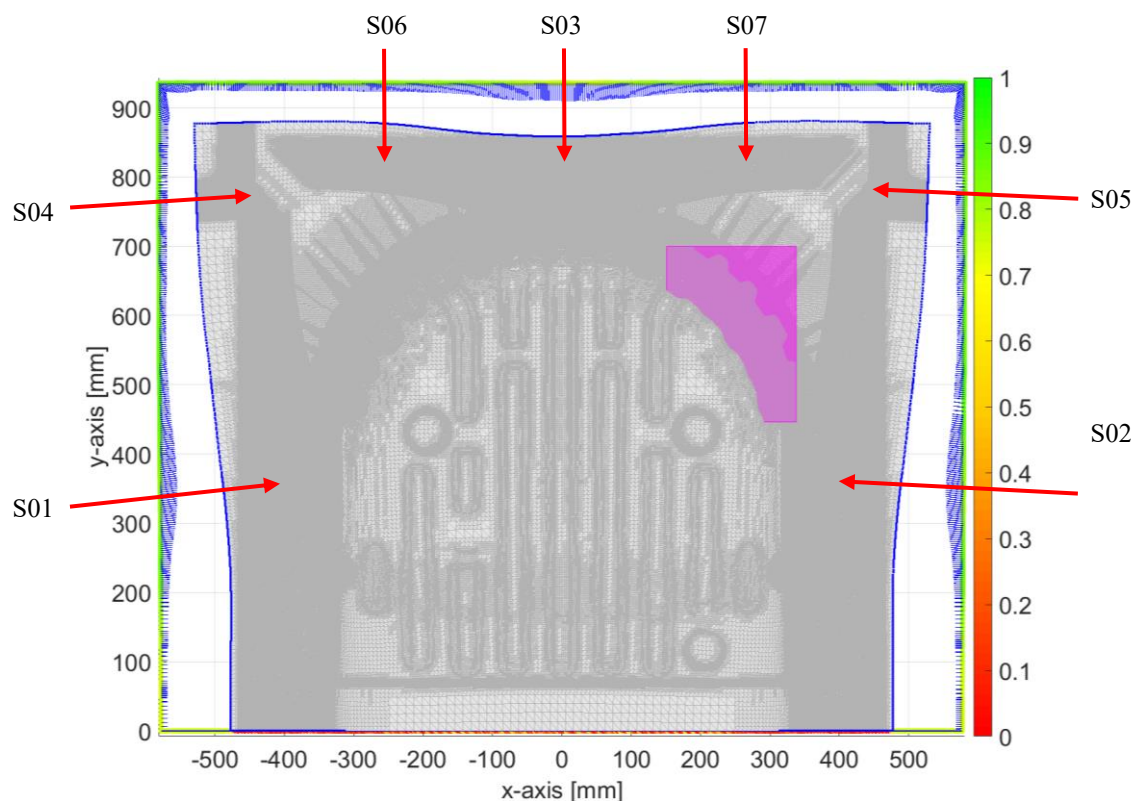

Figure 10. Evaluation of draw-in sensor positions (the shown geometry is the baseline simulation).

The results of such calculation are shown in Figure 10. Red arrows mark possible sensor positions, the green contour around the part shows the correlation between a selected quality criterion (green – correlation value 1: perfect correlation, red – correlation value 0: uncorrelated) and the blue area marks the variation of the draw-in (the length of the blue lines shows the variation range). In Figure 10, rupture risk in the marked are is selected as the quality criterion. As can be seen, the correlation between the quality criterion and the draw-in is very high all around the contour. The draw-in variation is changing along the circumference. For the measurements a larger variation is better since it will result in an increased robustness. Sensors 2, 3, 5 and 7 are selected for further examinations.

5. Virtual test bench
In Simuplan, a virtual test bench is implemented in order to investigate the behavior of forming processes and do a first test of the control system. For this purpose, the changing process parameters

must be defined. At first only the closed loop control is tested. Therefore, the friction coefficient is changed depending on the stroke number. The other parameters, like the mechanical properties or the blank position, are kept constant. From part 1 to part 500, a linear increase of the friction coefficient is assumed (Figure 11). The only parameter, that can be changed by the control system in this application is the binder force.
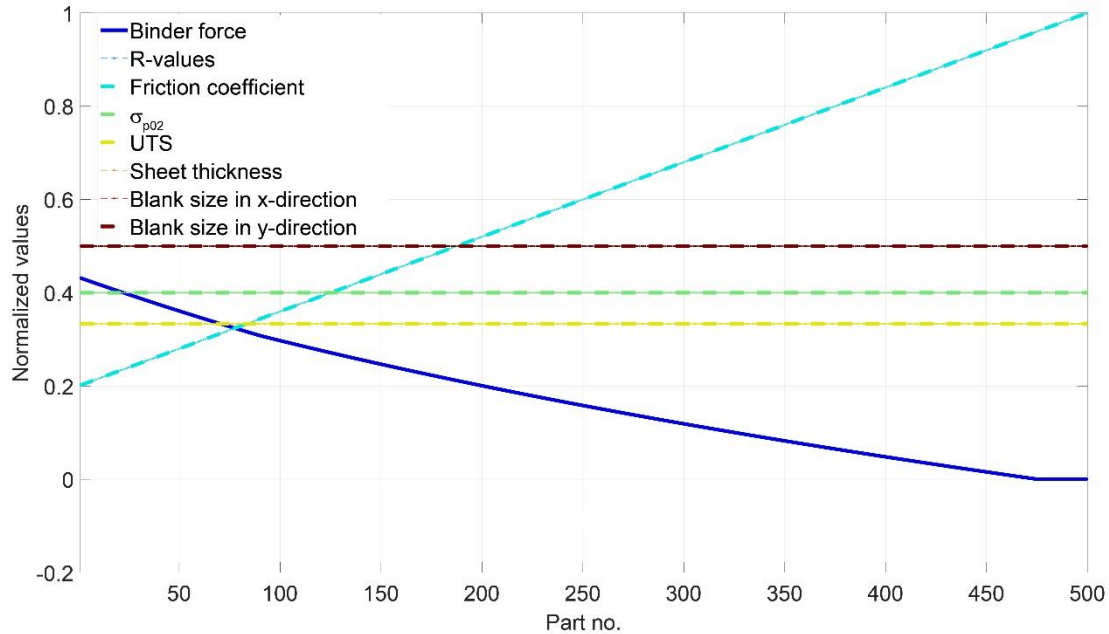

Figure 11. Changing process parameters friction coefficient (cyan) and binder force (blue).

When the tool is warming up, the friction coefficient increases. The control system then reduces the binder force to adapt the process to the instantaneous conditions and keep the draw-in in the specified range.
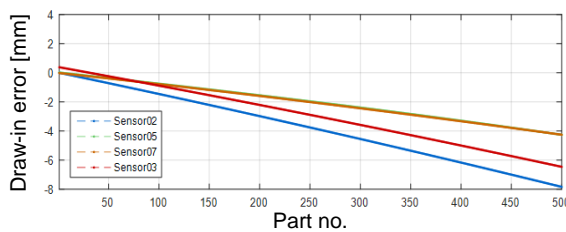

Figure 12. Draw-in without control system (binder force stays constant).
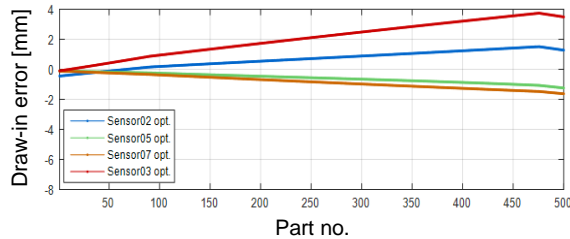
Figure 13. Draw-in with closed loop control adjusting the binder force.

Figure 12 shows the draw-in of the first 500 parts of a batch without using the closed loop control. With a higher temperature, friction increases and the draw-in decreases (the draw-in decrease is in a range of 4 mm to 8 mm, depending on the measuring position. In Figure 13 the draw-in with the use of the control system is shown. The draw-in at two positions is slightly increasing, but stays within an acceptable range of +/- 4 mm. The reason for this behaviour is the fact, that the control system can only use the global binder force to adapt the process. There is no locally acting binder force in the simulation model used. This results in a smaller draw-in error, but prohibits the system from reducing the error to zero. Another scenario is a warm-up phase with an interruption, e.g. because of quality problems of the part (Figure 14).
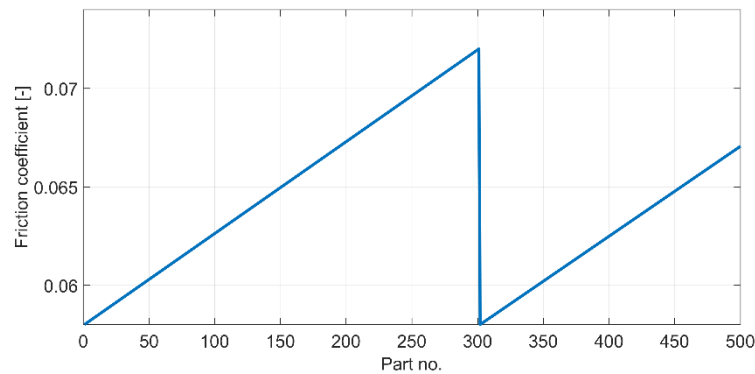
Figure 14. Friction coefficient during warm-up phase with a production break.

In such a case a drop of the tool temperature will occur resulting in poor part quality when the process recommences. The friction coefficient and therefore also the draw-in values change compared to the values before the break as it is shown in Figure 15. In Figure 16 rupture risks 01 and 04 are shown.
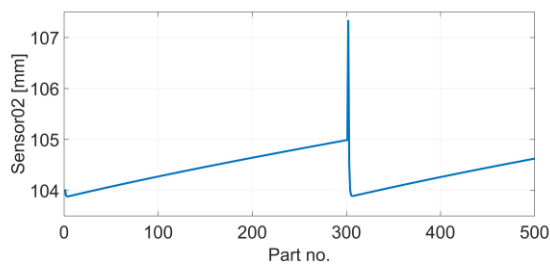

Figure 15. Draw-in of sensor 02 after production interruption (without open loop control).
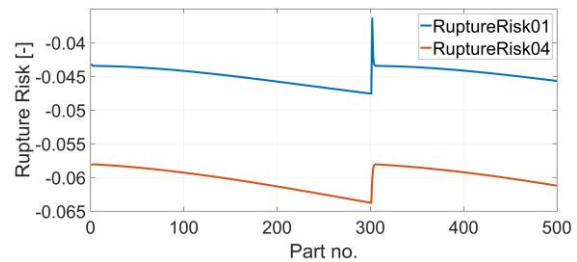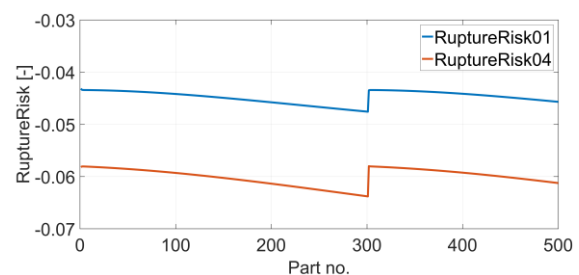

Figure 16. Rupture risks 01 and 04 with interruption (without open loop control).

Rupture risk 04 will be critical (> -0.04) when production recommences. By using the control system the draw-in step after the break is eliminated (Figure 17) and rupture risk 04 also remains uncritical as shown in Figure 18.
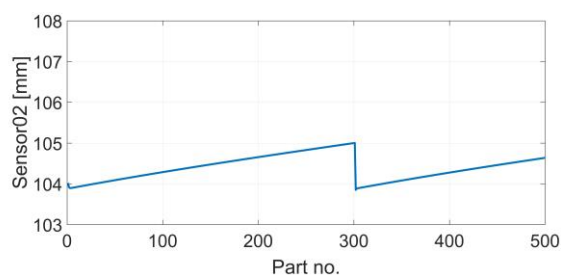
Figure 17. Draw-in of sensor 02 with control system (closed loop and open loop).

Figure 18. Rupture risks 01 and 04 with control system (closed loop and open loop).

6. Conclusions and outlook

It was shown that a control system based on numerical simulations and the in-line acquisition of the tool temperature and the draw-in is capable of keeping a forming process in specified limits. Based on variant simulations metamodels can be calculated that describe the forming process and contain the knowledge generated in the numerical simulations. An unstable process with a small process window can be significantly improved. The next step in the project will be a more detailed simulation with locally adapted friction settings using the TriboForm software.

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