

## OBSERVABILITY OF QUALITY FEATURES OF SHEET METAL PARTS BASED ON METAMODELS

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**Abstract.** Deep drawn sheet metal parts are increasingly designed to the feasibility limit, thus achieving a robust process is often challenging. The fluctuation of process and material properties often leads to robustness problems. Especially skid impact lines can cause visible changes of the surface fine structure even after painting. Numerical simulations are used to detect critical regions and the influences on the skid impact lines. To enhance the agreement with the real process conditions, the measured material data and the force distribution are taken into account. The simulation metamodel contains the virtual knowledge of a particular forming process, which is determined based on a series of finite element simulations with variable input parameters. Based on these metamodels, innovative process windows can be displayed to determine the influences on the critical regions and on skid impact lines. By measuring the draw-in of the part, sensor positions can be identified. Each sensor observes the accordant quality criterion and is hence able to quantify potential splits, insufficient stretching, wrinkles or skid impact lines. Furthermore the virtual draw-in sensors and quality criteria are particularly useful for the assessment of the process observation of a subsequent process control.

### 1 INTRODUCTION

The fluctuation of process and material properties, as well as changing environmental conditions and the increasingly tighter tolerance requirements, often lead to robustness problems during series production [1][2]. The factors influencing robustness are not measured systematically, thus online action is limited to a manual intervention on a trial-and-error basis. The major disadvantages are the quality of the outcome is strongly correlated to the experience of the staff and eventual corrections are costly. Furthermore additional circumstances, such as

the reduction of the material thickness, complex geometries with sharp radii and the flexible choice of the press, limit the process stability even further.

The goal of the project is to inspect the critical regions at an early stage regarding robustness problems and to propose improvement measures based on the metamodels. By the use of accurate material models based on experiments, the implementation of digitized tool geometries and the consideration of the press construction, the significance and illustration accuracy of the simulation can be increased.

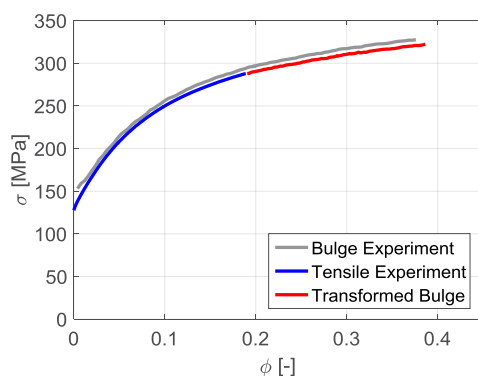
With the AutoForm version R7 it is possible to compute skid impact lines [3]. Another aim is to identify the influences on the simulatively determined quality criterion and to find a strategy how to avoid skid impact lines without cost-intensive rework and without using die inlets only by changing the press settings.

## 2 PROCESS DESCRIPTION

The front mudguard by Daimler shows critical behaviour in production, e.g. splits, insufficient stretch respectively hardening through minimal thinning and skid impact lines. Especially variations of the material properties through different batches of blanks have a large impact on the quality of the part. In particular the influence on skid impact lines is very pronounced. Therefore the simulation accuracy is enhanced through a variety of different arrangements.

### 2.1 Material model

The part is made out of aluminium AA6014 from Novelis (AC170). To approximate the material behaviour various experiments are used in a material model. The tensile experiments are used to capture the characteristic flow behaviour in rolling direction. With additional tensile experiments in  $0^\circ$ ,  $45^\circ$  and  $90^\circ$  to rolling direction, the anisotropy coefficient, yield stress, tensile strength and equivalent strain are measured.



**Figure 1:** Flow curves of tensile and bulge experiments

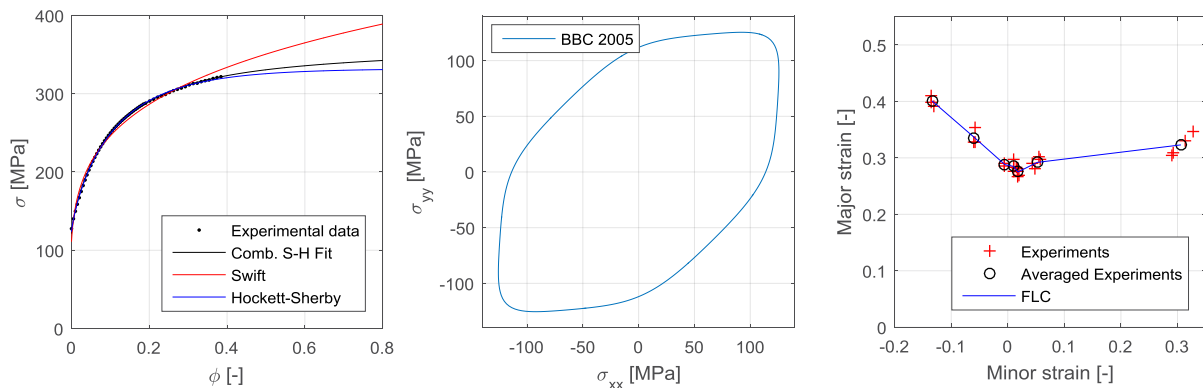
This figure above shows the biaxial flow curve (grey). To enhance the prediction of the flow behaviour the biaxial stress state is transformed into a uniaxial stress state, by means of the principle of equivalent work [4]. The flow curve is then fitted with a combined S-H approach (Swift and Hockett-Sherby) [3]. The yield locus is fitted with the BBC model for the measured

data at room temperature. The M-value of the yield locus is assumed to be 8 because of the face-centered cubic crystal structure. The measured values of the anisotropy and of the stress ratios are listed in table 1. The ratio between the biaxial and uniaxial stress state is evaluated at 4% of logarithmic strain because of the measurement uncertainty at the beginning of the bulge test.

**Table 1:** Measured anisotropy and stress ratios for yield locus

Anisotropy	Values	Stresses	Values
$r_0$	0.714	$\sigma_0$	113.8 MPa
$r_{45}$	0.498	$\sigma_{45}$	112.7 MPa
$r_{90}$	0.711	$\sigma_{90}$	111.9 MPa
$r_b$	1	$\sigma_b$	118.4 MPa

The Forming Limit Curve (FLC) in Figure 2 (c) is measured by doing Nakajima experiments at room temperature. The evaluation method is based on the strain rate evolution by Volk and Hora (Volk 2011b) [5]. For each geometry at least three experiments are evaluated and then averaged. Finally the resulting points of the seven different types of specimen are connected with each other. The resulting line represents the limitation of the forming process because localized necking may occur.



**Figure 2:** Experimental and fitted flow curve (a), yield locus (b) and FLC (c)

## 2.2 Tool geometries

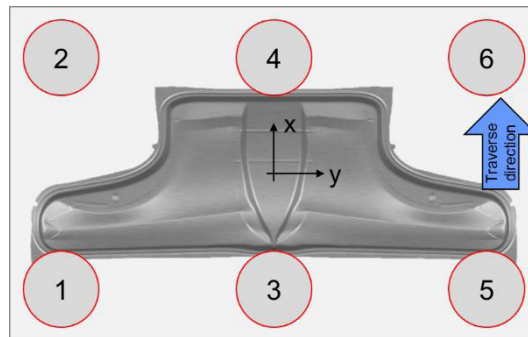
After the design of the die addendum and the drawbeads in the method plan, the tool geometries are milled. Afterwards the geometries have to be processed by hand in tool tryout. Especially the drawbead geometries respectively the restraining forces of the drawbeads are adapted to avoid splits, wrinkles, sink marks or skid impact lines. Thereby, in case of a split the drawbeads are smoothed locally to increase the draw-in. Furthermore originally designed radii in the punch and in the die are harmonised. Typically the tryout is done in many loops. After each loop the influences of the made adjustments on the part quality are checked in the tryout press. These quite intense modifications of the tool geometries lead to very different simulation results [8]. Hence, the tools are digitised when tools are ready for serial pressing. The

digitalization is made with a GOM ATOS measurement system. The finalized and re-meshed geometries have a tolerance of maximum 10 microns.

### 2.3 Press construction

In AutoForm the common simulation setting is to use an initial pressure which is distributed homogeneously. In reality the mechanical, single-acting press can be controlled over six die cushion forces, which transmit forces via cushion quills to the binder. Consequently they allow an inhomogeneous force distribution around the binder. Thus, the transmission of the binder force is adjusted in simulation in consideration of the positions of the cushion quills. This measure allows in simulation to redistribute the acting forces inhomogeneously on the binder surface by moving the force application point, in order to better map the set values on serial press [8].

In Figure 3 the positions of the six different die cushions is displayed.



**Figure 3:** Positions of hydraulic die cushions

The press settings of the six die cushion forces are listed in table 2.

**Table 2:** Die cushion forces of press

Die cushion nr.	Force [kN]
1 / 3 / 5	470
2 / 4 / 6	450

In simulation the die cushion forces of the die cushions 1, 3 and 5 are reduced because of symmetry to the position of die cushion 3. The same goes for the upper die cushion row to position 4. In simulation this simplification does not influence the simulation result because in AutoForm the tools are assumed to be rigid [3].

Hence, with these two cushion forces it is possible to change the total binder force and the force distribution. The force distribution is computed as a force delta between the lower and the upper die cushion rows (see figure 3). The relation is expressed in equation (1).

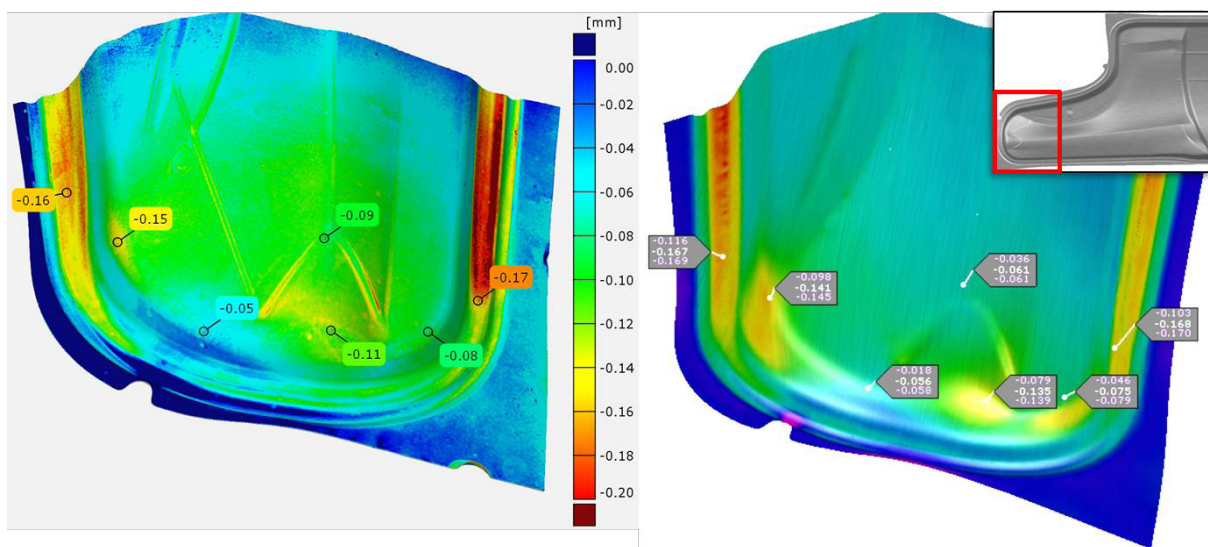
$$\Delta F = (F_1 + F_3 + F_5) - (F_2 + F_4 + F_6) \quad (1)$$

### 3 VARIATIONAL SIMULATION

Deep drawing processes are influenced by many different parameters, such as material properties, tool temperature and thus lubrication behaviour. In case the process becomes unstable, the press settings are adjusted. Thereby typical measures are to change the total binder force or the force distribution. Some press operators also change the lubrication amount. In order to model the behaviour of the part when any material or process parameters change, variant simulations are computed.

The range of variation of each parameter has to be defined carefully. The range should correspond to the fluctuations during serial pressing. If the range is too large, the simulation results are unrealistic, thus the metamodels will be distorted. If the range is too small, the metamodel does not map the entire range of fluctuations.

The defined fluctuation range should be varied around a suitable operating point [8], [7]. Therefore a part is removed during serial production after the first deep drawing operation and then compared with the simulation. The material used in simulation corresponds to the used batch of material in production. The friction coefficient, total binder force and force distribution are adjusted to fit the draw-in of the produced part. With these simulation settings the simulated thinning distribution is compared with the measured thickness reduction of the part (see Figure 4). The measurement is performed with a GOM ATOS system in two different regions of the part. The figure below shows one of the regions.



**Figure 4:** Comparison of thickness reduction between digitised part (left) and simulation (right)

The simulation result from AutoForm R7 is relatively close to the measurement. The deviations are mostly below 0.02 mm. Also the thinning of the material passing through the drawbead can be predicted by the simulation with a good accuracy. Differences in the thinning distribution are based on the simplifications in the simulation, such as the constant friction coefficient, the neglect of the tool deflection but also on the fluctuating initial blank thickness.

In view of the comparison of the thickness reduction, the equalized simulation is a suitable

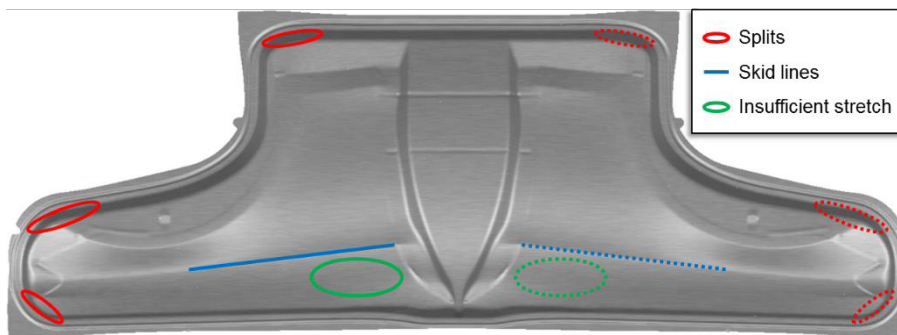
operating point for the variational simulations. The defined ranges are shown in the table below. The forces are specified based on different press settings during serial production, the friction coefficients based on experience [9] and the material parameters based on the suppliers material data sheets. The design of experiment with 96 simulations is automatically created in AutoForm R7 according to the Latin Hypercube Sampling with six independent variation parameters. Although the variations of yield stress and tensile strength correlate with each other, they are varied independently to simulate low-quality (high yield stress, low tensile strength) and high-quality batches of material.

**Table 3:** Variation parameters and range

Variation parameter	Minimum	Nominal	Maximum
Binder force $F_{\text{tot}}$	2'000 kN	2760 kN	2'800 kN
Force distribution $\Delta F$	-30 kN	60 kN	300 kN
Friction $\mu$	0.09	0.11	0.13
Yield stress $\sigma_{0,2}$	103.8 MPa	113.8 MPa	123.8 MPa
Tensile strength $\sigma_{\text{ts}}$	225.4 MPa	235.4 MPa	245.4 MPa
r-values ( $r_0, r_{45}, r_{90}$ )	-10%	0.71, 0.50, 0.71	+10%

### 3.1 Simulation criteria

In AutoForm R7 a wide range of result variables are available to quantify a potential quality feature in the part. For example splits can be detected by evaluating the result variables *Thinning* or *Max. Failure* (ratio of major strain to FLC). In the variational simulations three regions with risk of splits could be detected (see Figure 5). Additionally a skid line and a region with insufficient stretch below the skid line are identified to be critical. The criteria are slightly worse in the left half of the part (which corresponds to the mudguard on the right hand side of the car), which is why the following analyses are focused on the left side of the part.



**Figure 5:** Defined simulation criteria of part

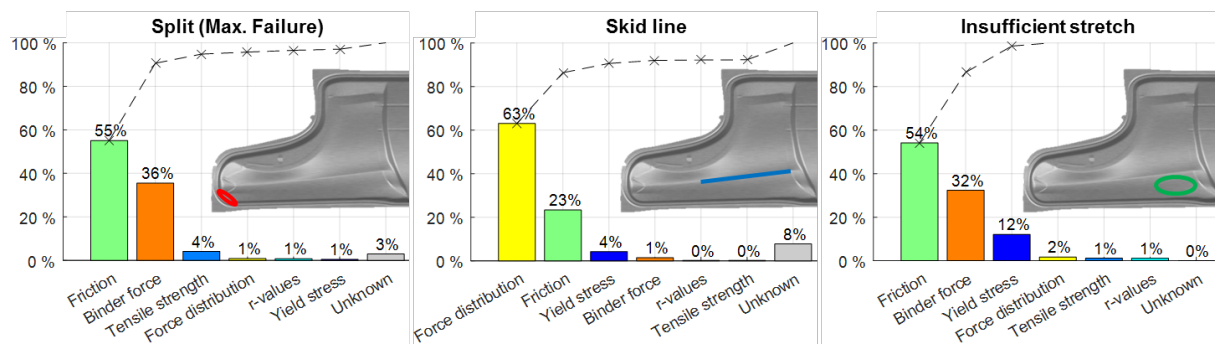
Skid lines represent damage to the sheet metal. They are clearly visible as scratch marks on the finished part. In case the material is dragged against sharp features of the tool after the first contact. They usually arise when the sheet is bended over a sharp angular feature and is subsequently pulled over this feature (e.g. drawbeads, die entry radius) or stretched over the top

of the punch (e.g. design features). If the skid lines are located in the visual range of the finished part, they should be avoided. By adjusting the binder force, changing the addendum design or the retention force of the drawbead through geometrical adaptations, the movement over the radius can be reduced. Thus, skid lines may be reduced or even avoided [3]. As the tools already exist and used for serial production, skid lines should be avoided without cost-intensive rework, therefore only by changing the press settings.

In AutoForm R7 skid lines are computed with two user defined analysis parameters: the maximum tool radius (curvature of tool) and the contact pressure between the tool and the sheet. If the curvature and the contact pressure exceed the predefined radius and pressure values in the same area, a skid line may occur [3].

After computing all simulations, the simulation criteria are defined for the different result variables. For each defined criterion a metamodel is fitted. The used types of metamodels are based on the *Response Surface Methodology*, whereby the polynomial degree is limited to a quadratic base model with interaction coefficients. Every metamodel is validated with the leave-one-out cross validation, to guarantee an appropriate model and to avoid an overfit.

Based on the metamodels the influences of the varied parameters on the defined criteria are quantified by using sensitivity analysis. The applied method is the *Fourier Amplitude Sensitivity Test* (FAST) [10]. The resulting sensitivities are shown in Figure 6.



**Figure 6:** Sensitivities on splits (a), skid impact lines (b) and insufficient stretch (c)

The sensitivities for split criterion (Figure 6 a) point out the friction and binder force to be the most relevant parameters, which is a plausible behaviour. Furthermore the tensile strength shows a relatively small sensitivity. The higher the tensile strength is, the smaller the risk of splits. A similar behaviour could be identified for the insufficient stretch, apart from the not negligible dependence of the yield stress. The higher the yield stress is, the smaller will the stretching in this region turn out. The skid line conversely is primary depending on the force distribution. The metamodel suggest that an increasing friction, due to rising tool temperature during serial pressing, could be corrected by changing the force distribution.

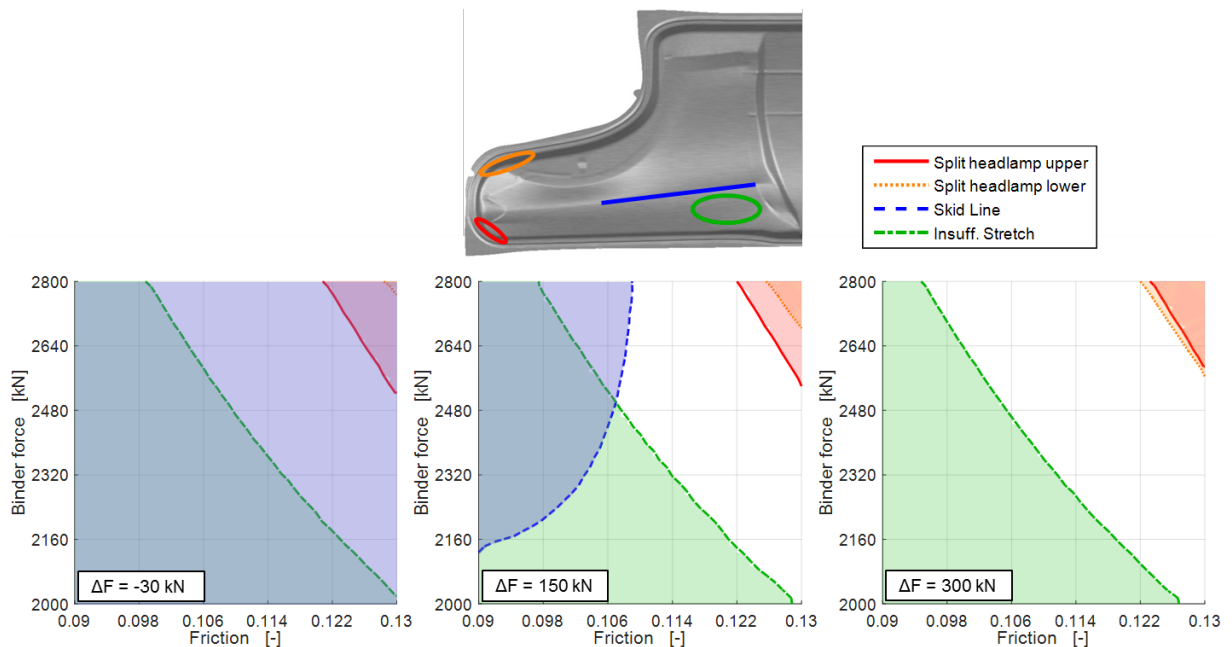
### 3.2 Process window

In the current state of the art different process windows can be displayed, such as one- and two-dimensional process windows based on conservative minimum/maximum analysis, convex hulls and multi-dimensional hypercubes parallel to the axes. For each of these simplification

methods some information gets lost [11], [12].

Every simulation criteria and hence every metamodel is limited by an upper or lower limitation value, e.g. splits, more specifically the result variable from AutoForm *Max. Failure* [3], at 70% of the major strain in the FLC. By keeping the material properties and the force distribution at a constant value, the metamodel of the criterion is reduced to a three-dimensional surface in dependency of the binder force and the friction. The defined limitation value can now be visualised as a contour line. The projection of this line in the plane of the two remaining parameters (binder force and friction) illustrates the process boundary regarding this specific simulation criterion (see Figure 7, process boundary in red).

This approach is repeated for the remaining simulation criteria and provide further process boundaries. Skid lines are limited at 15 mm (process boundary in blue) and the insufficient stretch criterion at 1% thinning (process boundary in green). (*Note: These limitation values do not necessarily correspond to reality, because the simulation settings can significantly change the numerical results. However, the simulation behaviour shall be assumed to be similar to the real process behaviour.*)



**Figure 7:** Process windows for different force distributions

The sensitivity analysis (see Figure 6) already pointed out, that the force distribution does not strongly influence the split and the insufficient stretch criteria. The skid lines conversely are significantly affected by changing force distributions. This behaviour can also be observed in Figure 7: If the forces on die cushions 2, 4 and 6 are increased respectively reduced on 1, 3 and 5 (see Figure 3), the skid lines might grow. To avoid skid lines the die cushion forces 1, 3 and 5 should be increased.

At the beginning of the serial production, the tools are cold and thus the friction is low. To reach nevertheless a sufficient stretching for the first part, the total binder force should be



increased at the beginning of the production. After the tools warm up and thereby the friction increases, the binder forces have to be reduced. Otherwise the process would run into risk of splits.

The shown process windows in Figure 7 are only valid for the pre-defined batch of material (see table 3 for nominal material properties). As soon as the material properties change, the process boundaries and thus the process window alters.

### 3.3 Influence of material on process windows

The fluctuations of the material properties in different batches of material can be very pronounced. Therefore the influences on the process window have to be analysed individually. For this two additional batches of material with various formability are exemplarily analysed. The resulting process windows are shown in Figure 8 below.

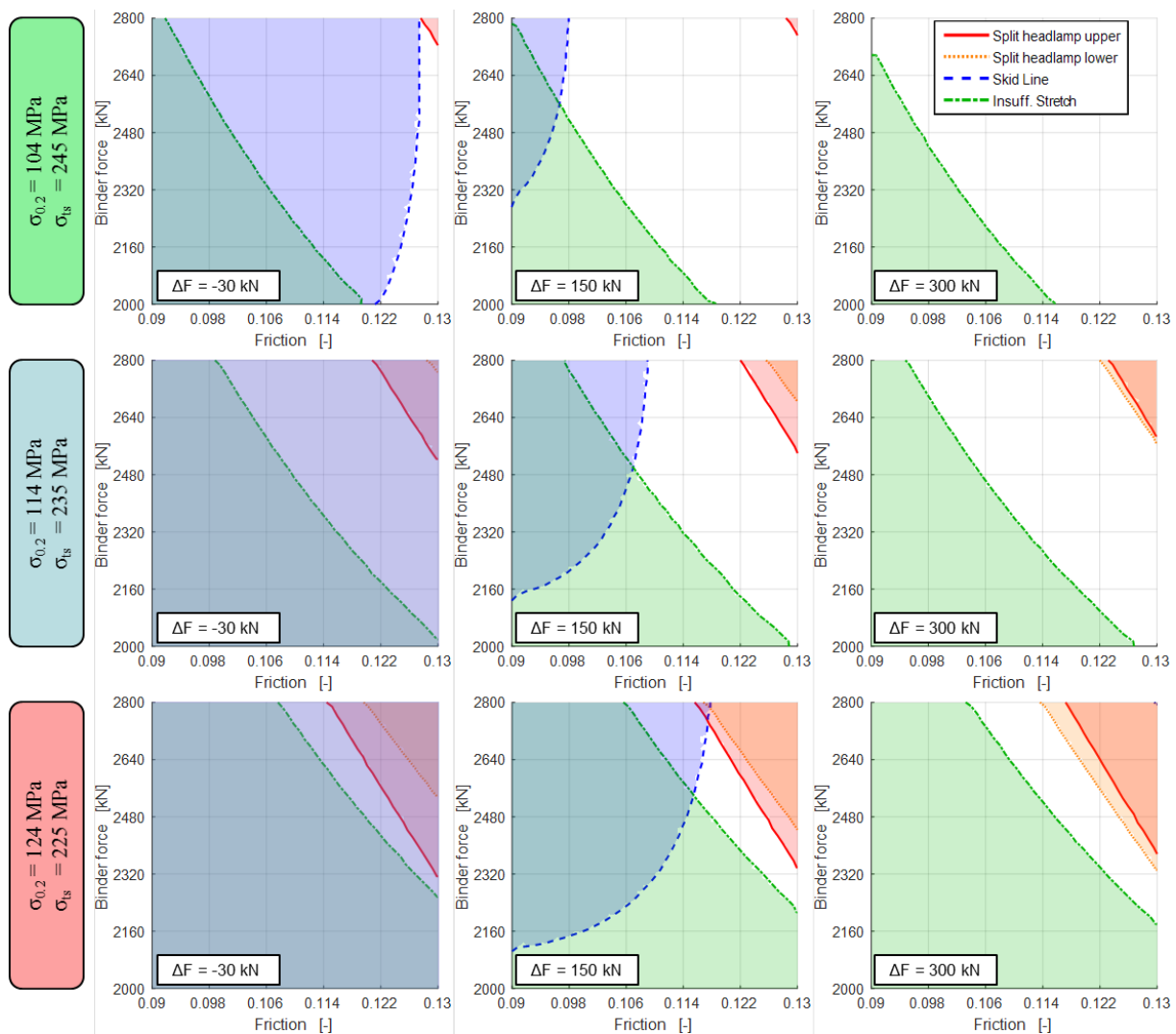


Figure 8: Process windows for three batches of material with different formability

In case a material batch with good formability characteristic (combination of low yield stress and high tensile strength) is used in production, risk of splits are very small. Also the process boundary due to insufficient stretch become less critical. Thus the process window gets bigger the process is more robust.

A material batch with bad formability characteristics (combination of high yield stress and low tensile strength) affects negatively the process boundaries. Although the skid lines can be avoided, the risk of splits and insufficient stretch are getting worse. The remaining process window becomes pretty narrow. Therefore the robustness is reduced, because small changes in friction lead to either risk of splits or insufficient stretch. Hence, the press settings should be adjusted more frequently.

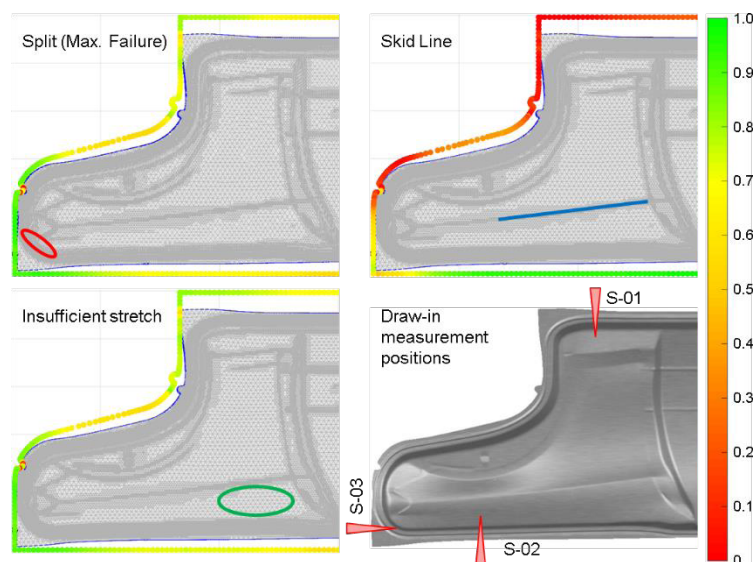
Apart from that, the two different split criteria (red and orange) react differently to the force distribution. While the orange split criterion is getting worse for higher force deltas, the red one is not really affected. For large force deltas the orange split criterion is getting more critical compared to the red split criterion.

#### 4 APPLICATION OF METAMODELS FOR PROCESS CONTROL

During serial pressing the quality criteria cannot be quantified as the simulation does. The part contains either a split or not. A precise statement about a numerical value (e.g. thinning of the material) is associated with high expenditures and costs. A much less expensive and more flexible approach is to measure the draw-in of the part optically in order to enable a quality assessment. For that it is essential to locate the draw-in measurement positions, which allow a reliable conclusion about the defined criteria in the part.

##### 4.1 Selection of draw-in measurement positions

Based on the variation simulations in AutoForm the correlation between the draw-in and the values of the different simulation criteria are calculated [8]. For each criterion the correlations are displayed in colour around the part (see Figure 9).



**Figure 9:** Absolute draw-in correlations and resulting draw-in measurement positions (on bottom right)

The selected draw-in measurement positions are placed in the regions with good correlation values over 0.75 with as many criteria as possible. Consequently some criteria can be observed by more than one draw-in measurement, which increases reliability (see table 4). To fully observe the detected simulation criteria of this part, three measurement positions are sufficient.

**Table 4:** Correlation values between virtual draw-in sensors and simulation criteria

<b>Simulation criterion</b>	<b>S-01</b>	<b>S-02</b>	<b>S-03</b>
Split headlamp	-0.75	-0.7	-0.91
Skid line	-0.03	0.94	0.7
Insufficient stretch	0.79	0.72	0.88

On the basis of the variational simulations the virtual draw-in measurements are fitted with metamodels. They contain the virtual knowledge how the process settings have to be changed in case the friction increases due to rising tool temperatures or in case another batch of material is processed.

#### 4.2 Feed forward and feedback control

The previously generated knowledge of the process can be used in a feed forward approach to improve the part quality even before the feedback loop would be able to react. The feedback loop is used to compensate all non-measurable effects, such as changing friction conditions due to rising tool temperatures. Therefore the metamodels are evaluated [13].

If another batch of material is processed with different material properties, the strain distribution in the part, and thus the draw-in would change. To suppress a shift in draw-in and to keep the same part quality, the forces have to be adjusted. These adjustments are evaluated based on the corresponding draw-in metamodels [13]. The material properties are measured with an eddy-current measurement system [14].

## 5 CONCLUSION

With the newly released AutoForm version R7 it is possible to generate all required simulation criteria, though not transferable one-to-one to reality as numerical values. But the behaviour respectively the influences on the criteria can be modelled with sufficient reliability.

Multidimensional systems with different influencing parameters and complex relationships are very difficult for the press operator to get oriented trustworthy and to adjust the press settings accurately in case of any changes in the process. Therefore process windows are used to visualise the influences of the input variables on the simulation criteria. This kind of visualisation simplifies the understanding of the process and provides assistance to adjust the press settings.

For a subsequent process control the simulation results are adequate, because the metamodels are able to map the behaviour of the different input parameters on the draw-in. The metamodels provide a first approach how the press settings should be changed, before the part is produced. Changes in non-measurable effects, such as changing friction conditions, can be corrected based on the metamodels with a feedback control.

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