Prediction and assessment of skid line formation during deep drawing of sheet metal components by using FEM simulation

P Cyron1*, M Liewald1

1 Institute for Metal Forming Technology, University of Stuttgart, Holzgartenstr. 17, 70174, Germany

* patrick.cyron@ifu.uni-stuttgart.de

Abstract. The subjective perception of the quality of sheet metal components mainly depends on geometric characteristics and surface structures. In this context, particular attention must be paid to avoiding surface defects such as skid lines during the sheet metal forming process for components with high surface quality requirements (e.g. outer skin passenger car panels). In principal, FEM simulation can provide an effective tool for predicting such surface defects. However, the numerical modelling approaches available today do not yet allow an adequate basis for assessing their quality relevance in production, which especially applies to skid lines. In a previously published study, new skid line criteria were developed in this regard, considering unbending strain, thinning and major strain. Using a simple steel sheet part (DC06) as reference, the study showed that these criteria allow the quality relevance of skid lines to be predicted relatively accurately. This paper focuses on the validation of the proposed skid line criteria and their applicability to the materials DC06 and AA6016. Furthermore, the numerical studies presented show that one of the novel skid line criteria, which considers unbending strain and thinning, is able to accurately locate and predict the quality relevance of skid lines even for complex shaped parts.

1. Introduction
In recent years, the challenges in automotive production regarding sophisticated, brand-defining design specifications as well as outer skin surface quality standards have increased rapidly [1]. While premium manufacturers have distinguished themselves in past decades by technological leadership, for example in terms of efficient engine design, improved driving safety and lightweight body design, these technical aspects of vehicles today are increasingly converging across brands and vehicle segments [2]. As a result, premium car manufacturers nowadays additionally stand out from their competitors due to their high-quality craftsmanship and the high surface quality of outer skin car body panels. It is well known, that design awakens the emotionality of a vehicle and is a key sales argument [3]. In order to ensure the quality of a vehicle body in terms of its appearance, the relevant quality characteristics of surface and shape (contour), flushness and gap dimensions of outer skin sheet metal parts must be considered thoroughly [4,5,6,7]. Therefore, analytical and numerical methods are used today to achieve a high surface quality of such dimensional part characteristics during the very early product development process. Here, compensation strategies are developed in order to ensure specified gap dimensions or the flushness of component subassemblies and to avoid tolerance fluctuations occurring
during the assembly of component groups [8,9]. Furthermore, the manufacturability as well as the appearance quality of folding loops can be predicted numerically or analytically, thus increasing the quality of vehicle bodies with regard to gap dimensions between outer skin parts [2]. Even irreversible shape deviations of the vehicle body that occur during paint drying processes can be numerically predicted and evaluated in order to develop suitable strategies to compensate these scatter in production [10].

According to [3], FEM simulation is also used to predict surface defects such as skid lines on unpainted car body components. Such skid lines are caused by an unbalanced draw-in of the part flange and thus by an undesired relative movement of the sheet metal material over structural edges or small radii in the center area of the punch surface. As a consequence, this leads to a linear plastic bending deformation, which is an offset of the sheet cross section by a few micrometers and can be optically perceived as a line, depending on the angle of view [11,12,13]. When considering strain in the sheet metal, it can be noted that the greater the ratio between sheet thickness and tool radius, the greater the strain. By correlating this observation with the restraint force or stress, the so-called skid line limit diagram (SLLD) may be obtained (Fig. 1a)). It clearly shows that the skid line only occurs within a certain load range. The much larger area of the SLLD marks a kink [14]. Wani intradul et al. [14] therefore divide the resulting surface defects into two categories: kink and skid line. Thereby, the local curvature of both sides of the sheet appear equivalent in case of a kink, whereas skid lines do not show the same curvature on both sides (Fig. 1b and c)). In contrast to a kink, however, skid line areas show a significant change in sheet thickness. Therefore, thinning is used for predicting skid lines in the FE simulation in [3].

![Figure 1. Kink and skid line. (a) Skid Line Limit Diagram (SLLD), (b) representation of the kink and (c) the skid line [14].](image)

Skid lines are often unavoidable for interior or structural components of vehicle bodies, but do not cause visible surface defects relevant to quality and therefore do not lead to scrap. However, if such surface defects arise on the outside of outer skin parts, in many cases this may lead to scrap. Thus, deep drawn parts showing skid lines in the central area in many cases will be rejected, since reworking them is too cost intensive. In general, once skid lines have occurred, they can only be eliminated by time-consuming and cost-intensive reworking of the respective tool [11].

Today, FEM simulations can only predict skid lines on unpainted body parts, although the final paintwork of parts usually leads to a significant increase in their visibility. Thus, no direct statement can be made about the quality relevance of a skid line of the painted part [3]. For this purpose, experimental investigations with the material DC06 were carried out to determine a data basis for a subsequent numerical study. This study showed the correlation between the skid line and the state variables unbending strain (ubs), thinning (thin) and major strain (ms). The combination of the mentioned state variables resulted into two skid line criteria (ubs/thin and ubs/ms), which showed a meaningful correlation with the offset of the skid line. Subsequently, the comparison of the numerical and the experimental results showed the predictability of the skid line by the mentioned evaluation criteria [15]. However, it must be considered that the experiments in these investigations are based only on a specimen representing a uniaxial stress state. In reality, however, superposed stress states can occur during the forming process. For this reason, the work presented in this paper investigated whether the new evaluation criteria are capable to accurately predict the quality relevance and the position of the skid line considering a multi-axial stress state during deep drawing.
2. Experimental study

2.1. Experimental set-up and procedure

In order to verify the criteria for evaluating the quality relevance of skid lines developed in [15], a test tool was developed with a punch geometry featuring three-dimensionally curved surfaces (see Figure 2). The CAD model of this test tool is shown as a cross-section in Figure 2 a). In comparison to the experimental tool in [15], this is a closed tool with the same tool frame in order to save manufacturing costs. The dimensions of the tool inserts (die, blankholder) are given by 296 mm x 276 mm.

![Figure 2. a) CAD-Model and b) experimental tool made of steel.](image-url)

For the recording of the blankholder and punch force, piezo load cells were integrated into the tool. For measuring the blankholder force, piezo cells were integrated into each of the four drawing pin extensions (PE). In this way, the process force was measured separately at each drawing pin and summed up to the resulting blankholder force after the test. The punch force was recorded using two load cells located below the tool punch. The sum of these two load cells resulted in the acting punch force.

The punch geometry (dimensions: 169 mm x 64 mm) featured a concave and convex curved surface in order to test the skid line criteria under consideration of a multi-axial stress state (see Figure 3). In addition, this geometry represents a critical component area with respect to the skid line, which can be found for instance on doors, hoods or tailgates of modern vehicles. Thus, the evaluation criteria could be verified on the basis of a complex and realistic component geometry.

![Figure 3. Schematic sketch of punch nose of the experimental tool with its dimensions.](image-url)

For the experimental investigations, the punch nose radius \( r_P \) of the tool was varied between 1.0 mm and 5.0 mm. The opening angle \( w_t \) 120°, which was directly influence by the drawing depth of 19.0 mm. Preliminary numerical investigations have shown that the radii \( r_{cx} \) and \( r_{cv} \) of 70.0 mm were suitable for the investigations, since skid lines could be generated by means of this geometry on the one hand, and on the other hand no cracks occurred in the test components for the investigated sheet metal materials DC06 (\( s_0 = 0.7 \) mm) and AA6016 (\( s_0 = 1.0 \) mm).

The experimental test procedure involved applying Raziol CLF 200 E lubricant with 1 g/m² on the test specimens of the material DC06 before each test. The test specimens of the material AA6016 had already been coated with Hotmelt E1 by the manufacturer. The blankholder forces for both materials were varied between 100 kN and 200 kN. By varying the blankholder forces, skid lines with different offsets could be generated. Using an octagonal blank, the test specimens shown in Figure 4 were produced. All the generated skid lines occurred in the area marked in yellow.
Following the experimental procedure, all test specimens were evaluated with regard to the visibility and the offset of the skid line along with the blank draw-in. The evaluation regarding the visibility of the skid line was carried out by a test person survey.

### 2.2. Influence of painting on the visibility of the skid line for components with curved surfaces

A total of seven of the manufactured test components made of DC06 and AA6016 were coated by cathodic dip painting under conditions of current painting technology in the automotive plant in order to investigate the influence of painting on the visibility of the skid line. In Figure 5, an unpainted and painted test component manufactured with a blankholder force $F_{BH}$ 200 kN is compared. On the unpainted part, a skid line is clearly visible below the sharp tool radius, as on the painted part.

![Figure 5. Deep drawn part: a) not painted and b) painted](image)

Furthermore, the test components were evaluated visually by 10 test persons before and after the cathodic dip painting. The test persons were asked whether they could recognize a skid line in the area below the sharp tool radius. Once this had been clarified, the test persons measured the offset of recognized skid line. The results of this survey are shown in Figure 6. Here, the red bars represent test components with skid lines and the green bars test components without. The orange bars, on the other hand, show the difference between the component assessment in the unpainted and painted state.

For example, the cathodic dip painting of the test component No. D4 resulted in the skid line being recognized by all test persons compared to the unpainted state. Since this test component showed a relatively long offset, the skid line was clearly visible to the test person in the painted state.

![Figure 6. Results of survey of optical inspection of unpainted and painted components of materials a) DC06 and b) AA6016.](image)
The result of the test component No. D5 does not represent a clear result in comparison to the other test components, as only a slight majority of decisions was achieved. The skid line of the test component No. D5 appeared quite close to the punch radius, therefore it was only recognized by a small majority of the test persons on the painted component. Since no clear tendencies could be identified from this result, the result of the test component No. D5 was considered with reservations.

In addition, the results displayed in Figure 6 showed the influence of the punch radius $r_p$ on the skid line. Thus, small punch radii ($r_p \leq 2.5$ mm) of the experimental tool led to clearly visible skid lines on the surface of the test components, except for the test component No. A5 (see Figure 6b)). This was due to the fact that the skid line occurred very close to the punch peak and it was difficult for the test persons to distinguish between the transition area of the punch radius to the concave surface and the skid line. For a punch radius $r_p$ of 5.0 mm under the same experimental conditions, no skid line was detected on the sheet metal component surface by the test persons, except for test component No. D5 already mentioned above.

Using the experimentally obtained data described in Chapters 2.1 and 2.2, the FEM models and evaluation criteria presented in Chapters 3 and 4 were validated.

### 3. Modelling and numerical study

In order to verify the developed skid line evaluation criteria [15]:

$$\text{Criterion}_{SL-1} = \frac{\text{abs}^2}{\text{thin}}$$  \hspace{1cm} (1)

$$\text{Criterion}_{SL-2} = \frac{\text{abs}^2}{\text{ms}}$$  \hspace{1cm} (2)

the experimental investigations were numerically modeled using the simulation software AutoForm R8. For this purpose, a FE model was created for each punch radius $r_p$. The set-up of the FE model shown in Figure 7 a) consisted of a punch, a blankholder and a die. The position and dimensions of the blank in the simulation corresponded exactly to the real sheet blank (116 mm x 196 mm), which had an octagonal shape. The material data of the materials DC06 ($s_0=0.7$ mm) and AA6016 ($s_0=1.0$ mm) are depicted in Table 1.

![Figure 7](image)

**Figure 7.** a) Set-up of the FE model, b) numerical result regarding blank draw-in.

| Material | $s_0$ (mm) | E-Modulus (GPa) | Yield Strength (MPa) | UTS (MPa) | U.E. (%) | n (\%) | $r_m$ (\%) |
|----------|------------|------------------|----------------------|-----------|---------|-------|-----------|
| DC06     | 0.7        | 206              | 161.3                | 296.8     | 22.3    | 0.213 | 2.03      |
| AA6016   | 1.0        | 70               | 118.9                | 236.4     | 22.2    | 0.274 | 0.542     |

The element type selected was an elastic-plastic shell element (EPS) with 11 layers. A master element size of 5.0 mm was selected for the FEM model, equivalent to 7647 elements. All other input parameters are listed in Table 2. The optimized friction coefficients of the FE models are shown in Table 3.
Table 2. Input parameters for the FEM models.

| Input parameters          |              |
|---------------------------|--------------|
| Radius Penetration        | 0.22 mm      |
| Max Element Angle         | 15°          |
| Max Refinement Level      | 8            |
| Master Element Size       | 5.0 mm       |
| Initial Subdivision Level | Half         |
| Element Type              | EPS-11       |
| Thickness Stress          | On           |

Table 3. Friction coefficients for the FEM models.

| Material                   | Friction coefficient µ | Lubricant    |
|----------------------------|------------------------|--------------|
| DC06 (s0 = 0.7 mm)         | 0.14                   | Raziol CLF 200 |
| AA6016 (s0 = 1.0 mm)       | 0.11                   | Hotmelt E1   |

The FEM models were validated based on the experimental results of the sheet-metal draw-in (see Figure 7 b)) and the punch force. The FEM models showed good agreement with the experimental test results. This is exemplified for the sheet-metal draw-in “L” and “R” (see Figure 7 b)) in Figure 8.

Figure 8. Blank draw-in a) “L” and b) “R” for the material DC06 with a punch radius \( r_p \) 1.0 mm.

4. Results and discussion

According to [15], \( \text{criterion}_{SL,1} \) (\( \text{ubs}^{2}/\text{thin} \)) and \( \text{criterion}_{SL,2} \) (\( \text{ubs}^{2}/\text{ms} \)) were confirmed as suitable evaluation criteria for predicting the quality relevance and localization of skid lines. Both criteria differ mainly in the fact that \( \text{criterion}_{SL,1} \) considers thin (thinning) and \( \text{criterion}_{SL,2} \) considers ms (major strain). For the verification of the criteria, different parameter combinations (see chapter 3) were numerically computed. The limit values \( k_{SL,\text{Limit}} \) of the two evaluation criteria, which were derived from the survey, are listed in Table 4.

Table 4. Limit values of the evaluation criteria for the materials DC06 and AA6016.

| Criterion            | DC06 | AA6016 |
|----------------------|------|--------|
| \( \text{criterion}_{SL,1} \): \( k_{SL,\text{Limit}} \) | 0.16 | 0.18   |
| \( \text{criterion}_{SL,2} \): \( k_{SL,\text{Limit}} \) | 0.15 | 0.28   |

For the material DC06, Figure 9 clearly shows that \( \text{criterion}_{SL,1} \) localizes the skid line more precisely than \( \text{criterion}_{SL,2} \). Especially for a punch radius \( r_p \) of 2.5 mm, the experimental and numerical computed offsets of the respective skid line are almost identical. For a punch radius \( r_p \) of 5.0 mm, it can be observed that the \( \text{criterion}_{SL,2} \) localizes the skid line more precisely when a blankholder force of 200 kN is applied.
(test components No. D5). However, at this point it must be mentioned that this was the test component No. D5 already described in chapter 2.2. Consequently, the experimental result of this component has to be considered with reservations. For the material AA6016, the skid line was predicted exactly by criterionSL,1 for all punch radii. The results in Figure 9 show that criterionSL,1 is more suitable than criterionSL,2 for the localization of skid lines. In particular, it should be emphasized that for the material AA6016 at a punch radius of 2.5 mm, criterionSL,1 accurately predicts the skid line at the lowest blankholder force of 100 kN (test component No. A5). Thus, this criterion is capable to cover the special case of this test component, which was already mentioned in chapter 2.2.

![Figure 9](image)

**Figure 9.** Experimental vs. numerical results of the material DC06 and AA6016 for the punch radii \(r_P\) 1.0 mm, 2.5 mm and 5.0 mm.

In general both criteria are capable of predicting the quality relevance of a skid line. Nevertheless, criterionSL,1 is also preferred here, since it localizes the skid line more precisely. In order to evaluate how well the criterionSL,1 performs in comparison to existing skid line criteria, it was compared with the existing "AutoForm Skid Line Tool". Hence, a real, unpainted test component was compared to the corresponding FEM simulation with the two applied evaluation criteria (see Figure 10). Both criteria localize the skid line below the sharp tool radius precisely. However, the criterionSL,1 predicts the corner areas of the real test component more accurately. The AutoForm Skid Line Tool, on the other hand, overestimates the corner areas and detects a skid line that does not exist in reality (see Figure 10). Furthermore, the AutoForm Skid Line Tool predicts skid lines for process parameter combinations \((r_P \geq 2.5\) mm) for which the test components did not show any skid lines. This comparison demonstrates that the developed criterionSL,1 is capable to predict more accurately the quality relevance and localization of skid lines with respect to a painted part.

**a) Unpainted test component**

![Image](image)

**Figure 10.** Comparison of a) real unpainted test component with the corresponding b) FEM-Model with the developed CriterionSL,1 and the AutoForm Skid Line Tool.
5. Conclusion and outlook
By experimental and numerical investigations presented in this paper, two new evaluation criteria regarding the accurate prediction of the offset and the quality relevance of skid lines were verified on unpainted as well as painted sheet metal parts. Thereby, the test component showed a multi-axial stress state during the forming process. A test tool was developed with a punch geometry that features concave and convex surfaces. Experimental investigations were carried out with the materials DC06 and AA6016. Subsequently, the manufactured test components were painted and evaluated by means of a test person survey with regard to the visibility of the skid line. Based on the experimentally determined data, the subsequent numerical study was carried out. This study demonstrated that the quality relevance and position of the skid line on a component with curved surfaces was predicted using the developed evaluation criteria. In particular, the evaluation criterion based on unbending strain and thinning predicts the quality relevance of the skid line and its offset most accurately, even compared to the AutoForm Skid Line Tool.

The proposed evaluation criterion enables for instance the process planner to be supported at an early stage in the product development process. This is particularly important with regard to the design of deep-drawing tools for the production of outer skin components of a vehicle body. Since any skid line occurring in the component are visible to the customer and would therefore lead to scrap. The presented criterion now enables the method planner to predict quality-relevant skid lines already in the FE simulation. Thus, necessary optimizations can be carried out on the tool before its production in order to avoid the occurrence of skid lines and the associated cost- and time-intensive reworking of the deep-drawing tool.

In future investigations, the developed criterion should be analyzed regarding their transferability to other materials and complex component geometries. In particular, it should be considered for different outer skin components of a vehicle body which have critical areas with regard to the skid line.

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