



# Investigations of batch fluctuation regarding tribological conditions in series production of car body parts

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## Abstract

Fluctuations of material properties are one reason for the occurrence of cracks and waviness in series production of car body parts. Especially fluctuating tribological conditions have an effect on the friction behavior and thus on the material flow. So far fluctuating material properties are not considered in the standard FE-simulation and consequently not in the tool design. In order to enhance the accuracy of the simulation result and thus improve the tool design regarding a robust process, the appearance of batch fluctuations has to be consistently understood. Therefore, the impact of varying lubricant quantities and roughness have been investigated. Several batches have been analyzed to identify the main influencing parameter regarding the friction behavior. Flat strip-drawing tests have been performed to determine the friction coefficient. The investigations have been performed by using material from the series production, as delivered. Since the amount of lubricant turns out to be the main influencing factor, the characteristics and appearance of the lubricant distribution has been analyzed in a further step. The analysis has shown that the distribution of the lubricant changes within one coil over the coil width and length. In addition, the time of storage has been identified as one main influencing factor on the homogeneity of the lubricant distribution over the coil width. Based on these findings, a method has been developed to map the series production conditions regarding the friction conditions in the simulation. Hence, simulations were performed using a side frame blank with different friction conditions, to investigate the impact on the forming result. The results reveal that by considering realistically existing tribological conditions, more scrap is to be expected compared to the conventional simulation. This leads to the conclusion that previous simulation results are too optimistic. Consequently, the introduced method offers the potential to optimize the tool design by considering fluctuating tribological conditions already in the process of development. Thus, it is possible to reduce scrap and increase productivity.

**Keywords** Tribology · Material · Friction

## Introduction and state of the art

Driven by legal requirements to reduce CO<sub>2</sub> emissions, the automotive industry is facing new challenges. One of many options is to reduce the weight of the car body in order to reduce fuel consumption and consequently CO<sub>2</sub> emissions [1]. This is achieved for example by reducing the material

thickness of the car body parts. In addition, there are increased demands of the customers. This includes for example, a characteristic design that is reflected by sharp edges and small radii on the body shell [2]. These geometries are challenging regarding the forming process, so that the car body parts are designed at the limits of feasibility. Thus, the process window for the production of parts in good quality is small, not yet considering batch fluctuations, which may influence the forming result. Consequently, a further challenge in series production of car body parts is the occurrence of fluctuating material properties, including the sheet thickness, mechanical properties, sheet roughness as well as the amount and distribution of lubricant. These can lead to quality problems like cracks, thinning as well as wrinkling during the production process which causes scrap and rework of rejects. In order to increase the productivity and to produce car body parts in good quality, batch fluctuations have to be consistently

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understood and further have to be considered in the development process of the design of the tools. Furthermore, batch fluctuations are only rarely taken into account in the simulation and consequently in the tool design as well. So far, ordinary material models which are based on a small number of material properties are used, which reduces the accuracy of the forming result in the simulation [3].

Until now, there is only a limited knowledge about batch fluctuations regarding the material properties of rolled products used in series production of car body parts and its impact on the forming process. Material scatter regarding the mechanical properties of a large amount of coils have first been investigated by Wiebenga et al. [4] for robustness analysis. Experimental and numerical investigations have been carried out based on material of 41 coils, which has been characterized by 17 material parameters. The investigations demonstrate the effect of material scatter by experimentally performed cup tests, whose forming results have been reproduced by means of numerical cup tests. Held et al. [5] investigated the occurrence of changes of the formability due to material fluctuations within a coil. Sturm [6] analyzed several mechanical parameters regarding its fluctuation and its impact on the forming results. However, investigations on series car body parts have shown that the tribological properties of the blanks may not be neglected.

Especially, fluctuating material properties regarding the tribological conditions are not yet adequately understood. Hence, knowledge about batch fluctuations offers the potential to make the tool design more robust. The occurrence of fluctuating lubricant distribution on rolled products is recently introduced by Mohr et al. [7]. They suggest washing and re-oiling after cutting to length. Due to environmental reasons washing processes are no longer common. An alternative is offered by dry lubricants, which allow a homogeneous distribution of the lubricant layer [8], but lead to additional effort. Neumann [9] investigated fluctuations of the roughness over the coil length by extracting several samples over the coil width of one coil, concluding that no significant fluctuations can be determined. Analyses of a large number of batches were not carried out. Groche et al. [10] illustrate that several material properties as well as the tool properties have an influence on the tribological system and have to be considered as a whole. These include for example material-sided the sheet coating, the surface topography and the lubrication and tool-sided the coating and tool surface. Particularly with regard to the improvement of the FE-simulation, the tribological interdependencies have to be clarified. Sgarabotto et al. [11] investigated two types of lubricant in combination with three different roughness values by use of a flat strip drawing test, showing that the friction coefficient for the dry lubricant is lower than for the liquid lubricant. The effect of the sheet roughness on the friction behavior is

ambiguous. In sheet metal forming mixed lubrication is present, which represents a transition zone between boundary lubrication and hydrodynamic lubrication. Consequently, the influence of roughness could be relativized by the effect of hydrodynamic lubrication, which indicates an entire separation of the friction partners. The effect of different lubrication types under several sliding velocities has been investigated by Fu et al. [12], demonstrating that with an increasing sliding velocity the friction coefficient decreases in particular under dry condition and boundary lubrication. Filzek [13] presents results of strip drawing tests considering amongst other influencing factors the tool temperature. These show that by increasing the tool temperature the friction increases. Furthermore, Filzek et al. [14] point out that for an exact FE-simulation friction curves as a function of contact pressure and sliding velocity are essential, since Coulomb's law of friction which is commonly used does not reflect the actual conditions. Matuszak [15] draws a similar conclusion adding that also the lubrication conditions have a major influence. Strip drawing tests under varying tribological conditions considering several amounts of lubricant and contact pressures in order to improve the FE-simulation accuracy have been performed by Zöllner et al. [16]. The results show that with increasing amount of lubricant as well as increasing contact pressures the friction coefficient decreases. Hol [17] developed a multi-scale friction model for sheet metal forming applications in which the friction behavior is described physically. This model takes into account the pressure, strain and temperature dependence of friction and allows different lubrication regimes to be considered by coupling a mixed lubrication friction model and a boundary friction model. Furthermore, it is possible to consider the surface topography of the sheet metal. Shisode et al. [18] build up on this model and investigated the impact of the surface topography as well as the impact of lubricant pressure, revealing the effect of the amount of lubricant and the roughness on the friction behavior. Azushima et al. [19] investigated the contact pressure dependence on the friction coefficient differentiating between three levels of contact pressure which reveals that an increasing contact pressure leads to a friction decrease. As already mentioned, the friction behavior is likewise influenced by the tool surface. Investigations of the friction behavior of several modified tool surface textures carried out by Hazrati et al. [20] and Sulaiman et al. [21] showing the possibility to decrease the friction by use of defined surface textures. Another approach to reduce friction is to coat the tool surface. Zhao and Tremmel [22] investigated several diamond-like carbon coatings, showing that friction can be reduced, in terms of lubricant-free processes.

Most of the present investigations serve to improve the simulation accuracy or are limited to investigations of variations in mechanical properties. In addition, most of the investigations are performed under laboratory conditions and are limited to a small amount of data.

Recently it has become possible to gather large data volumes of the before mentioned material properties by several inline measuring systems implemented in the coil line [23]. Hence, there is the possibility to perform analyses regarding the scope and reason of fluctuations. This knowledge is essential to improve the tool design in order to enhance the process robustness, which will lead to a more efficient production process and less scrap. In summary, the literature research has shown that there remain open questions since a fundamental understanding regarding the occurrence of fluctuating tribological material properties and their effect on the friction behavior is lacking.

In the present work, the results of investigations regarding fluctuating tribological material properties and its effect on the friction behavior are presented. In addition, the main factor influencing the friction behavior and the cause of its fluctuations are identified. Furthermore, the findings gained are transferred to the FE-simulation in order to investigate the effects on a series car body part. Hence, the method introduced in the following provides an opportunity to consider batch fluctuations and to improve in development process of car body parts.

## Methodology

The aim of the study presented in the following is to establish an understanding of batch fluctuations regarding tribological material properties and their effect on the friction behavior in production of car body parts, since these pose a challenge in terms of the part quality. On the material side, amongst others, the amount of lubricant and the roughness determine the tribological behavior [24]. Thus, the effect of fluctuating sheet roughness and fluctuating amount and distribution of lubricant on the friction behavior are investigated.

Although, the occurrence of fluctuations of material properties are well known, the appearance of batch fluctuations has not yet been consistently understood and are not considered in forming simulations, so far. Therefore, the appearance of batch fluctuations regarding the tribological conditions and consequently the friction behavior is analyzed using an experimental and numerical approach. Hence, a method to improve the tool design by increasing the robustness considering batch fluctuations, is developed. Consequently, less quality issues are to be expected in series production of car body parts in case of fluctuating material properties and thus the number of rejects may be reduced. Additionally, the intervention in the process could be reduced, which leads to less plant downtime and an increase of productivity. However, this does not only have an economical effect, but also an ecological one, since the rejected car body parts are recycled in order to produce new coils by using enormous amount of energy.

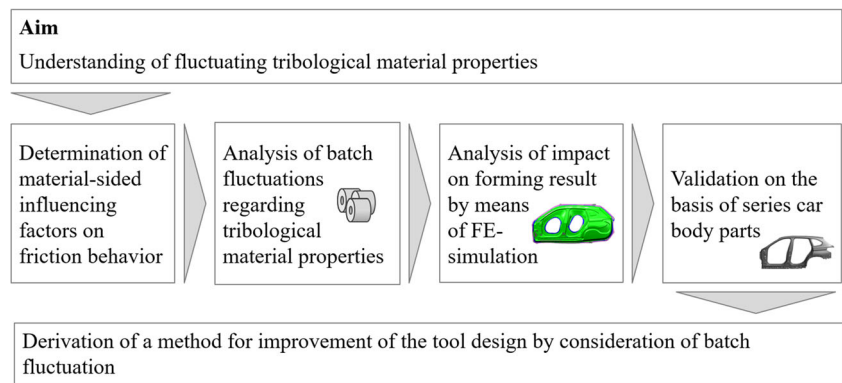
For the following investigations the side frame of the current BMW X1 has been used as reference part and experimental part since side frames are one of the most challenging car body parts. In order to identify the main influencing factor of the friction behavior, material from eight batches has been investigated in a strip-drawing test to determine the friction coefficient. In order to map the tribological conditions in series production, material from coils as delivered has been used. To cover the factory-set material specification, material from different batches has been analyzed, those material properties have been determined under laboratory conditions.

Inline measurement systems enable the acquisition of large amount of data regarding the material properties. Thus, in order to gain knowledge about the scatter range of the material properties, 129 coils for the production of side frame blanks have been analyzed by use of inline measuring systems. Furthermore, the cause of batch fluctuations with regard to the lubricant distribution is analyzed. The findings regarding the friction conditions have subsequently been used to gain knowledge about the impact of batch fluctuations on the part quality by using the FE-simulation. For this purpose, different friction conditions have been assigned to the blank to map the tribological conditions in series production of car body parts, similar to the approach of Tatipala et al. [25]. Moreover, the Coulomb's law of friction has been used in this context, since it is commonly used for industrial approaches. In a final step, a verification of the results is carried out on real car body parts. Previous studies often use the design of experiments method to analyze interactions of influencing parameters. The investigations described in the following are based on real process fluctuations occurring in the series process. Hence, it is possible for the first time to state the effect of batch fluctuations on the quality of car body parts. Figure 1 demonstrates the applied methodology.

## Experiment, data basis and simulation

Within this chapter, the experimental set-up of the strip-drawing test to investigate the impact of batch fluctuations on the tribological behavior and the approach are described. Furthermore, the material specification of the investigated batches and the available data basis for the analyses of the coils are presented. Additionally, the procedure for the data acquisition of the material properties, as well as the utilized measuring principles are introduced, in order to investigate the appearance of batch fluctuations by a large amount of data. In a final step, the gathered findings are used to analyze the impact of batch fluctuations on the part quality by applying the FE-simulation.

Fig. 1 Methodology



## Experimental set-up and approach

For the investigation of the friction behavior with regard to different tribological conditions which result from batch fluctuations, several batches of one supplier have been chosen to perform strip-drawing tests, since the material of one supplier is dedicated to one car body part. Therefore, blanks from several coils have been used to cover the possible range of roughness values between  $R_a = 1.10 \mu\text{m}$  and  $R_a = 1.60 \mu\text{m}$  due to the guidelines for car body parts. Consequently, material for the body shell have been used including blanks from the roof, door outer shell and side frames. The material for the roof and side frame blanks is a CR3 deep-drawing steel and the material of the blanks for the outer shell door is a CR180BH bake-hardening steel. All coils are coated with a hot-dip galvanizing of  $50 \text{ g/m}^2$  coating weight per sheet-side and have an electron discharge textured (EDT) surface topography. In general, the coils are delivered with an average coating of  $0.80 \text{ g/m}^2$  to  $1.00 \text{ g/m}^2$  of lubricant. Nevertheless, fluctuating lubricant quantities are to be expected due to a typical inhomogeneous lubricant distribution. In the following, this effect is named lubricant redistribution. Thus, for performing the strip-drawing test, blanks from series production have been taken to cut out samples. For each strip the amount of lubricant has been measured

at three positions on each side by a manual optical oil measurement system. Moreover, roughness measurements have been performed of each strip on the top and bottom side by a profilometer. These values have been averaged so that each strip is characterized by one roughness value and one value for the lubricant amount. Figure 2a) illustrates the positions of the extraction of the strips for measuring of the sheet roughness as well as for measuring the amount of lubricant by taking a side frame as an example. The strips of the door outer shell blanks and the roof blanks have also been extracted in rolling direction. Due to the different blank dimensions, between 5 and 11 strips have been taken from one blank. The geometry of the strips has the dimensions  $110 \times 700 \text{ mm}$  and are extracted at right angles to the direction of traverse. Moreover, friction jaws of the material GGG70L have been selected, since it is used in series production as well for the forming tools [2]. The friction jaws dimensions are  $80 \times 150 \text{ mm}$ . Furthermore, the friction jaws are uncoated and not hardened. The strips have been drawn with a velocity of  $400 \text{ mm/min}$  at  $2.0 \text{ MPa}$  contact pressure. Table 1 gives an overview of the used parameters and materials. A schematic set up of the strip-drawing test and the area of evaluation for determining the friction coefficient are shown in Fig. 2b). Based on this study it is possible to determine what the main influencing factor on the tribological

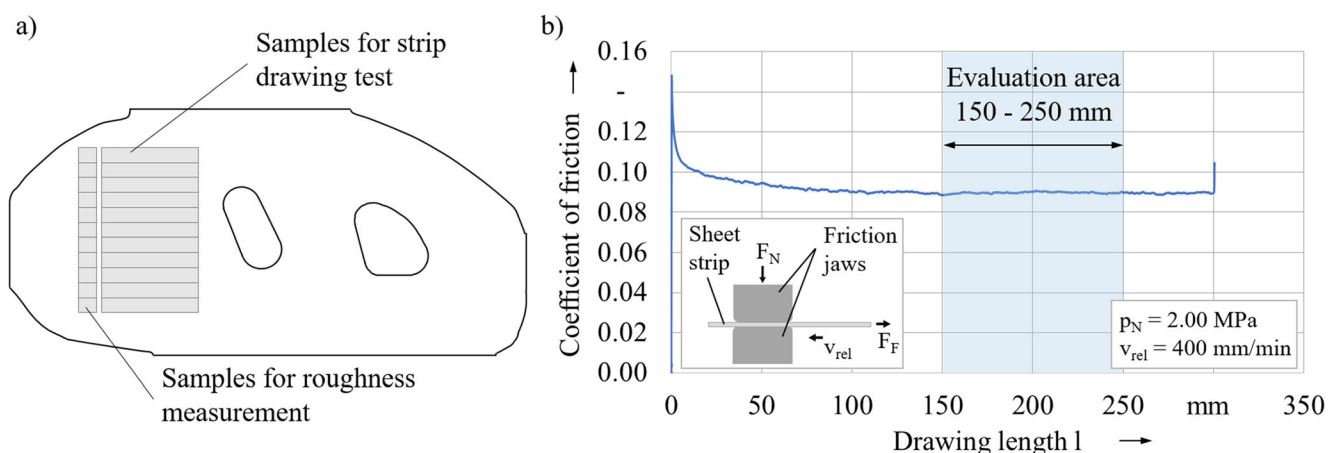


Fig. 2 Scheme of blank with position of samples for roughness measurement and strip drawing test (a) and schematic of strip drawing test and evaluation area for the determination of the friction coefficient (b)

**Table 1** Overview of experimental parameters and materials

<i>Batch</i>	<i>Part</i>	<i>Material</i>	<i>Strips</i>
1/2/3	Door outer shell	CR180BH	18
4/5	Roof outer shell	CR3	19
6/7/8	Side frame	CR3	30
<i>Parameter</i>	<i>Specification</i>		
Strip dimension	100 × 700 mm		
Friction jaw	80 × 150 mm		
Friction jaw material	GGG70L		
Velocity $v_{rel}$	400 mm/min		
Contact pressure $p_N$	2.0 MPa		

behavior is. In total 67 strips from 8 batches equivalent to 8 coils have been extracted and analyzed. Thus, the impact of varying tribological conditions on the friction behavior is investigated, covering a large spectrum of fluctuations.

### Data acquisition and data basis

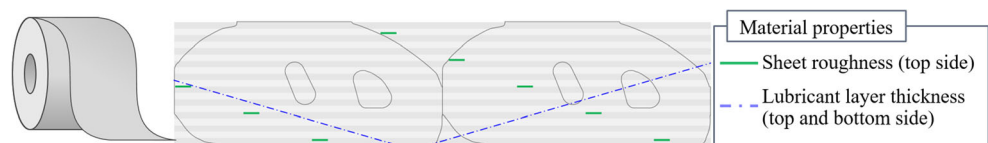
Recently, digitization has also found its way into the press plant [26]. Numerous contactless measuring systems make it possible to record material properties and thus also batch fluctuations already in the coil line, on the running strip. This information is allocated to a blank which can then be used for further processing steps. Besides the recording of the sheet thickness and mechanical properties, the tribological properties of the coils can also be recorded. For measuring the sheet roughness the laser based system SRM 100 by Amepa is used, which is based on the principle of triangulation [27]. The roughness is recorded on the top side of the coil, stepwise at five positions across the coil width over a length of 200 m. For the purpose of determining the amount and distribution of lubricant on top of the coils a traversing measuring system based on the principle of law of Lambert Beer's light absorption is utilized, which continuously crosses the surface of the coil [28]. The amount of lubricant is determined on the top side as well as on the bottom side of the coil. In order to simplify the evaluation and the demonstration the continuously determined values are dedicated to 20 tracks across the coil width. Figure 3 demonstrates exemplarily the measuring positions of the sheet roughness and the amount of lubricant, which are both measured along the entire coil. Thus, investigations of the coils regarding the appearance of fluctuations of the sheet roughness and the amount and distribution of lubricant can be performed on a large amount of data.

For investigating fluctuations regarding the sheet roughness and to ensure a comparability of the batches, coils from one steel supplier with an EDT surface topography and a hot-dip galvanized coating weight of 50 g/m<sup>2</sup> per side has been chosen. The database for the sheet roughness analysis of the coils comprises 11 coils of a structural car body part with a coil width of 1135 mm and coil lengths between 1547 m and 1705 m. The factory-set specification of the sheet roughness amounts between  $R_a = 1.30 \mu\text{m}$  and  $R_a = 1.80 \mu\text{m}$ .

Furthermore, the appearance and the characteristics of fluctuations with regard to the amount and distribution of the lubricant on the coil surface is investigated. Referring to the approach for analyzing the occurrence of fluctuations regarding the sheet roughness, 129 coils from one supplier with an EDT surface topography and a hot-dip galvanized coating of 50 g/m<sup>2</sup> have been chosen, in order to characterize the amount and distribution of the lubricant. The coils, used for the production of side frame blanks have been cut in a time span of 8 months. The material used for this study is a shell car body part, with a width of 1780 mm and an average length of 2587 m. In addition, the delivered coils are coated with the conventional anti-corrosion oil Multidraw PL 61 by Zeller+Gmelin having a viscosity of 58 mm<sup>2</sup>/s at 40 °C. Since the effect of lubricant redistribution at higher lubricant quantities is well known [7] the average quantity has been set to 0.80 g/m<sup>2</sup>.

The analyzed coils have been annealed between November 2018 and July 2019. The processing period from annealing at the rolling plant until the cutting into blanks in the coil line is between 12 and 70 days. Consequently, it is possible to analyze the influencing factor of the storage time on the redistribution of the lubricant.

**Fig. 3** Scheme of inline measuring positions of sheet roughness and lubricant layer thickness



## Simulation

So far fluctuating tribological conditions are not respected in the tool design and are thus only minor considered in the forming simulation. To evaluate the impact of fluctuating tribological conditions, the standard simulation has been adjusted to map the series conditions. For this purpose, the side frame of the current BMW X1 serves for investigating the impact of batch fluctuation as it is one of the challenging car body parts. Hence, for calculating the forming results the commercial simulation program LS-Dyna is used. The tool model is an already existing model whose individual components are available as rigid-body elements. This model has been used for the development of the series tools. Furthermore, the side frame is produced from CR3 deep-drawing steel for which, the BMW standard material modelling according to Barlat'89 with an exponent  $M = 2$  is utilized. Moreover, the numerical parameters for the investigations have been chosen according to Heinle [29] and the material data have been used as stated in the thesis of Fleischer [30]. The definition of the boundary conditions is derived from the present process parameters of the series production. A validation of the model was carried out by first checking the blank geometry and geometry changes to the tool, for example the radii of the draw beads. Furthermore, the flange draw-in of the real part was compared with the flange draw-in of the simulated part. Figure 4 presents the measuring positions of the flange draw-in. Changes to the blank holder spacing were incorporated into the CAD model to achieve a good accordance between the parts. An exact match is not possible due to the simplified conditions, such as a total force. In addition, deviations occur due to the blank position caused by the blank gauges. The measuring results of the flange draw-in are summarized in Tab. 2. With the exception of one measuring point, the deviations of the flange draw-in between the simulation and the real part are less than 10 mm. Nevertheless, the comparison shows a good agreement and is assumed as sufficiently accurate. In order to map batch fluctuations, the blank is divided into different segments, which are determined by the areas showing different tribological conditions by reference to the gained information from the fluctuating material properties data analysis. The friction coefficients determined in the strip-drawing test are used to assign different friction conditions to the blank.

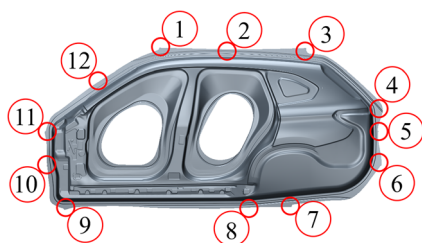


Fig. 4 Measuring positions of flange draw-in at side frame part

Table 2 Difference of geometry between simulation and real part

	Pos.1	Pos.2	Pos.3	Pos.4	Pos.5	Pos.6
Diff. in mm	9	4	5	10	0	7
	Pos.7	Pos.8	Pos.9	Pos.10	Pos.11	Pos.12
Diff. in mm	19	10	8	3	6	2

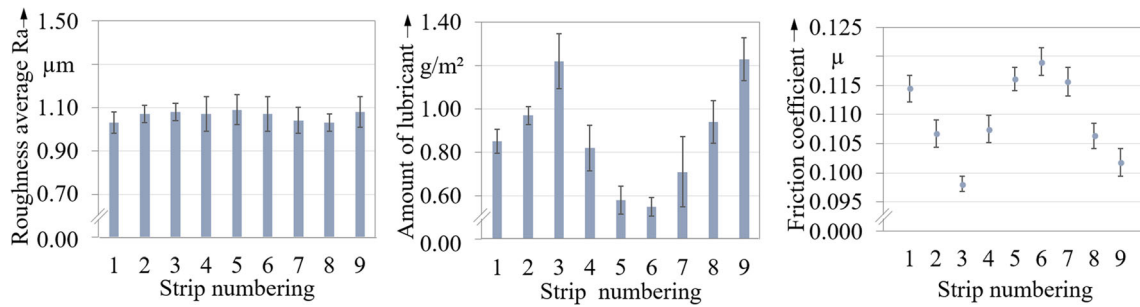
Since the coils are lubricated with  $0.80 \text{ g/m}^2$  of lubricant as standard, this value is used as a reference for the standard friction coefficient  $\mu_S = 0.12$ . In addition, the Coulomb's law of friction has been used, since it is the industrial standard approach. The appearance and extent of cracks, thinning and waviness serve as assessment criterion.

## Results and discussion

In order to improve the tool design the appearance of batch fluctuations and their impact on the car body part has to be known. Therefore, in the following chapter the results of the performed strip-drawing tests are presented. Furthermore, the findings of the appearance and scope of fluctuating material properties regarding the sheet roughness and the amount and distribution of lubricant are introduced. The knowledge gained from these experiments is transferred to the simulation, the results of which are finally presented.

### Strip-drawing test

In a first step the material properties as well as the determined friction coefficients have been analyzed batchwise and holistically in a second step. Figure 5 presents exemplarily the roughness values (a), the lubricant values (b) and the values of friction coefficients (c) of one of the investigated batches. The strip numbering displays the extraction position of the blank in coil width direction from the left hand side to the right hand side. Thus, strip 1 and strip 9 lie at the edge area of the coil. The standard deviation of the roughness values and amount of lubrication values results from the repeating measurements whereas the standard deviation of the friction coefficient results from all measured values within the evaluation area. The roughness values are between  $Ra_{\min} = 1.03 \text{ }\mu\text{m}$  and  $Ra_{\max} = 1.09 \text{ }\mu\text{m}$  and show no significant fluctuations. This finding is also confirmed for the other batches, for which the average standard deviation of the roughness values per batch is  $\sigma_{Ra} = 0.04$ . Furthermore, the finding of no significant fluctuation of the sheet roughness coincides with those of Neumann [9]. One reason for this could be that the skin pass rolls wear out slowly and homogeneously over the roll length. Since skin pass rolls can be used for several coils, changes are unlikely to be recognizable within one coil. Furthermore, no



**Fig. 5** Roughness values, amount of lubricant and friction coefficient values for one batch (CR3-Z100-EDT;  $l_{spec} = 0.80 \pm 0.30 \text{ g/m}^2$ ;  $Ra_{spec} = 1.10 - 1.60 \text{ }\mu\text{m}$ )

subsequent change in roughness, e.g. due to transportation is to be expected.

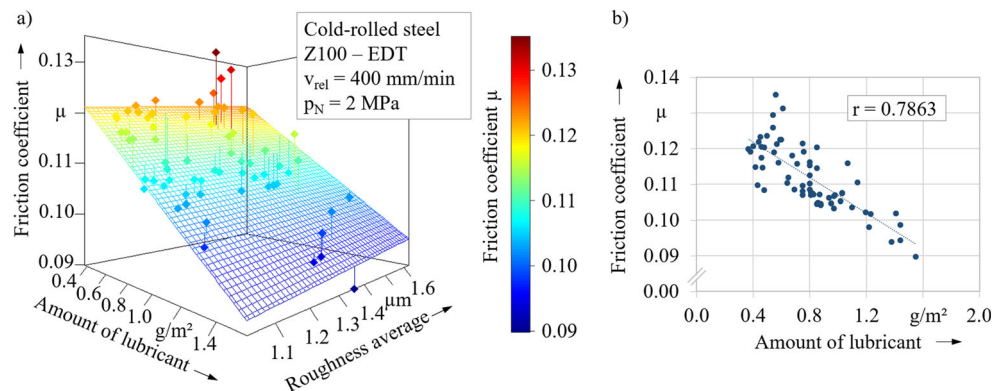
Compared to this, the values of the amount of lubricant show strong fluctuations. The values lie between  $l_{min} = 0.55 \text{ g/m}^2$  and  $l_{max} = 1.23 \text{ g/m}^2$  for the presented batch and exceeds the specification of  $l_{spec} = 0.80 \pm 0.30 \text{ g/m}^2$ . Due to the fact that the strips have been extracted over the coil width, this example shows a typical redistribution of the lubricant over the coil width, where the inner area of the coil is coated with less lubricant than the outer areas. This confirms the findings of Mohr [7], who firstly described the effect of lubricant redistribution. The surface pressure is assumed to be one reason for the lubricant escaping into the edge areas, since the thickness of the sheet is the highest in the middle of the coil. The different lubricant quantities are reflected in the coefficients of friction. Strip 3 and strip 9 show the highest amount of lubricant,  $l_3 = 1.22 \text{ g/m}^2$  and respectively  $l_9 = 1.23 \text{ g/m}^2$  and thus the lowest friction coefficients of  $c_3 = 0.098$  and  $c_9 = 0.102$ . Compared to this, strip 5 and strip 6 have the lowest lubricant quantity of  $l_5 = 0.58 \text{ g/m}^2$  and  $l_6 = 0.55 \text{ g/m}^2$ . The related friction coefficients are  $c_5 = 0.116$  and  $c_6 = 0.119$ . In total, the friction coefficients are between  $c_{min} = 0.098$  and  $c_{max} = 0.119$ . Thus, higher amounts of lubricant results in lower friction coefficients and reverse, which leads to a correlation coefficient of  $r = 0.94$ . These results show that the main influencing factor on the friction behavior is the amount of lubricant. The overall correlation coefficient of all eight batches is  $r_{total} = 0.79$  (Fig. 6b)) and show a strong correlation between the amount of lubricant and the friction coefficient.

Since not all batches show distinctive fluctuating lubricant values, the correlation coefficient is lower than the one of the previously shown single batch.

Due to the fact that, the roughness does not vary strongly, the impact of varying roughness can only be investigated by comparing several coils with different characteristics of roughness. Hence, a range of  $Ra_{total,min} = 1.03 \text{ }\mu\text{m}$  to  $Ra_{total,max} = 1.63 \text{ }\mu\text{m}$  of roughness has been covered. In addition, due to the effect of lubricant redistribution the lubricant quantities of the 67 strips vary between  $l_{total,min} = 0.37 \text{ g/m}^2$  and  $l_{total,max} = 1.55 \text{ g/m}^2$  lubricant, since the material has been used as delivered. Figure 6a) shows the friction coefficients as a function of roughness and lubricant quantity as a 3D-plot, highlighted by a linear plane to illustrate the result. It can clearly be seen that the variation of lubricant quantities has a strong impact on the friction behavior, whereas the roughness show no significant impact. The friction coefficients lie between  $c_{total,min} = 0.090$  and  $c_{total,max} = 0.135$  and illustrates the influence that the friction coefficient decreases with increasing lubricant quantities.

All in all, it can be stated that by having a constant roughness, the higher the amount of lubricant, the lower the friction. This can be explained by the fact that in case of a higher amount of lubricant the friction behavior changes from mixed lubrication to hydrodynamic lubrication, since the contact surfaces are more separated from each other. Furthermore, the spectrum of roughness in general is small, due to the factory-set specification. Consequently, the friction is only mildly effected by the roughness, whereas the amount of

**Fig. 6** 3D-plot of lubricant quantity, sheet roughness and friction coefficient (a) and correlation diagram of friction coefficient and amount of lubricant (b)



lubricant has a wider spectrum caused by its redistribution during storage and show a significant effect on the friction behavior. This again confirms the assumption that the hydrodynamic lubrication is dominant compared to the mixed lubrication.

Finally, the amount of lubricant can be identified as the significant influencing tribological material property on the friction behavior. Consequently, the scope of fluctuating lubricant quantities and distributions are analyzed in detail in the following chapter.

### Batch fluctuation

The investigations of the strip drawing test has shown that the lubricant has a significant impact on the friction behavior. Thus, in the following, the appearance of the amount and distribution of lubricant on the coils is analyzed on a large amount of data gathered by the use of inline measuring systems. In addition the appearance of batch fluctuation regarding the sheet roughness is analyzed.

### Roughness

For the sake of completeness, the fluctuations of roughness are investigated in the following. Thus, for analyzing the extent of batch fluctuations with regard to the sheet roughness 11 coils have been measured by an optical inline roughness measurement system. The measuring values function as an indicator for the roughness, since the roughness is measured indirectly and repeating measurements are not possible on a running strip. The roughness values are averaged by considering the measuring values of all five measuring positions over the coil width and coil length per coil. Figure 7 shows the measuring results of all 11 coils, for which the roughness specification is  $R_a = 1.30 \mu\text{m} - 1.80 \mu\text{m}$ . The roughness values lie between  $R_{a,\text{min}} = 1.50 \mu\text{m}$  and  $R_{a,\text{max}} = 1.60 \mu\text{m}$  and hence show no significant fluctuations. In addition, the standard deviation per coil lie between  $\sigma_{R_{a,\text{min}}} = 0.04$  and  $\sigma_{R_{a,\text{max}}} = 0.07$  and indicates that no noticeable differences are to be expected. Since the performed strip-drawing tests have not revealed a significant influence of the roughness on

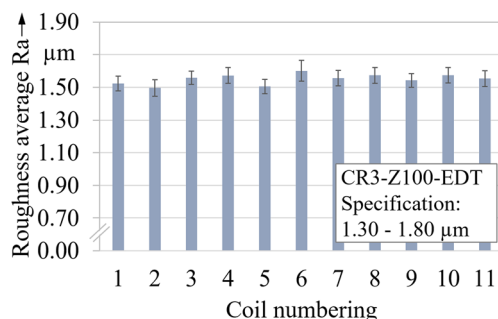


Fig. 7 Inline measured roughness values for 11 coils

the friction behavior, no further analysis are carried out at this point.

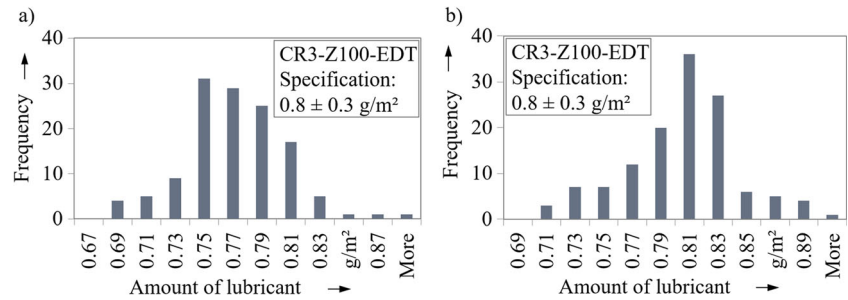
### Lubricant

Since the coils are coated on both sides with lubricant, possible differences between the top and bottom sides are analyzed in a first step. Therefore, the mean values of the lubricant quantity, determined over the coil length and width of the entire coil, are compared from the top and bottom sides of 129 coils. The measuring values are determined by an optical inline measuring system as described previously. Figure 8a) shows the frequency distribution of the mean values of the top side. Approx. 80% of the coils have an average lubricant value between  $0.75 \text{ g/m}^2$  and  $0.81 \text{ g/m}^2$ . A similar result can be seen for the bottom side (Fig. 8b)), where approx. 79% of the coils have an average lubricant value between  $0.77 \text{ g/m}^2$  and  $0.83 \text{ g/m}^2$ . Consequently, lubricant quantity values of all coils lie within the factory-set specification of  $l_{\text{spec}} = 0.80 \pm 0.30 \text{ g/m}^2$  lubricant per side. This effect was to be expected, since the same amount of lubricant is usually applied to both sides.

In a second step, in order to evaluate the distribution of the lubricant over the coil width, the values of each measuring track over the entire coil length are averaged. The comparison of the measurement results for two coils are shown in Fig. 9. Illustration a) shows the lubricant quantity for each of the 20 measuring tracks of one coil for the top and bottom side, where the amount of lubricant is homogeneously distributed over the coil width. The measured values for the top side lies between  $l_{\text{top,min}} = 0.60 \text{ g/m}^2$  and  $l_{\text{top,max}} = 0.98 \text{ g/m}^2$ . For the bottom side, the measured lubricant values range from  $l_{\text{bot,min}} = 0.61 \text{ g/m}^2$  to  $l_{\text{bot,max}} = 0.96 \text{ g/m}^2$ . The mean value of the lubricant quantity on the top side is  $l_{\text{top,mean}} = 0.71 \text{ g/m}^2$  respectively  $l_{\text{bot,mean}} = 0.74 \text{ g/m}^2$  for the bottom side. In addition, the correlation coefficient between the mean lubricant values over the coil length per measuring track between the top and bottom side amounts  $r_{1,1} = 0.958$ . Consequently, the amount and distribution of the lubricant can be assumed as equal for both sides. This accordance is confirmed as well for the second coil (Fig. 9b)). The lubricant quantities lie between  $l_{\text{top,min}} = 0.53 \text{ g/m}^2$  and  $l_{\text{top,max}} = 1.13 \text{ g/m}^2$  for the top side respectively  $l_{\text{bot,min}} = 0.55 \text{ g/m}^2$  and  $l_{\text{bot,max}} = 1.11 \text{ g/m}^2$  for the bottom side. Thus, the measured values for the top and bottom side show a similar range of lubricant quantity. However, the range of the lubricant quantity is larger for the second coil, which nearly reaches the lower tolerance limit of  $0.50 \text{ g/m}^2$  and exceeds the upper tolerance limit of  $1.10 \text{ g/m}^2$ . In this case, the lubricant shows a distinctive inhomogeneous distribution over the coil width. The measuring tracks 7, 8, 15 and 16 show the highest lubricant quantities, whereas measuring track 9 till 13, which lie in the middle of the coil, show the lowest amount of lubricant. Hence, the lubricant squeezes out from the inner area to the outer areas, due to



**Fig. 8** Frequency distribution of mean values of lubricant quantity for top side (a) and bottom side (b)



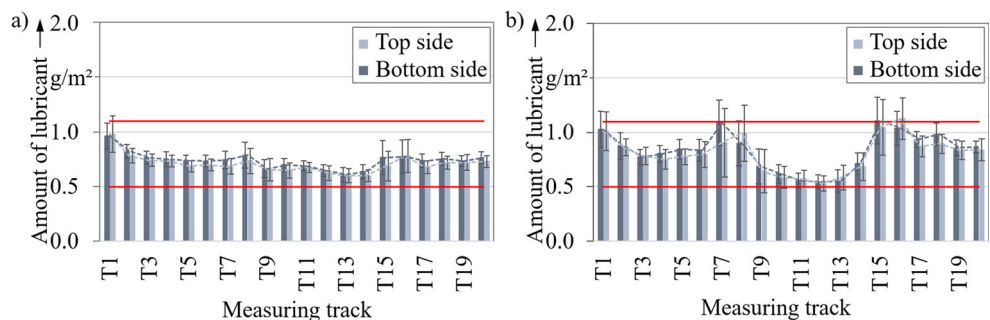
the crowning of the coils. These findings are reflected in the findings of Mohr et al. [7] who first describe the occurrence of lubricant redistribution. The correlation coefficient between the mean lubricant values over the coil length per measuring track between the top and bottom side amounts to  $r_{1,2} = 0.940$ . Hence, lubricant quantity and distribution show a strong correlation between the top and bottom side of the coil. Furthermore, the mean value of the lubricant quantity on the top side is  $l_{top,mean} = 0.81 \text{ g/m}^2$  respectively  $l_{bot,mean} = 0.83 \text{ g/m}^2$  for the bottom side. This reveals that the mean value is an inadequate assessment criteria for the lubrication conditions. The average correlation between the top and the bottom side determined by the mean values per measuring track for all 129 coils leads to  $r_{1,total} = 0.938$ . This indicates that if the lubricant distribution is known for one side, consequently also the lubricant distribution on the opposite side is known. Hence, the values of the lubricant amount of the top side is considered in the further investigations. However, differences of the amount and distribution of lubricant cannot be excluded entirely since different amounts of lubricant per side could be applied. Furthermore, production interruptions during the oiling process may lead to differences of the lubricant amount, as well. In the following the phenomenon of lubricant redistribution over coil width is investigated by questioning how the distribution behaves in coil length direction. In addition, the influencing factor regarding the cause will be analyzed. Therefore, the coils have been split into areas of 250 m in coil length direction, for which the amount of lubricant is averaged per track.

Figure 10 shows exemplarily the mean lubricant quantity values over the coil width at five positions of one coil over the coil length. At the beginning of the coil, from coil length 0 m

to 250 m the lubricant is homogeneously distributed over the coil width (Fig. 10a)), whereas towards the end of the coil (2201 m - 2250 m) the amount of lubricant shows a significant redistribution. In total, it can be seen that the redistribution of lubricant over coil width increases with increasing in coil length direction. Hence, with increasing coil length the inner area of the coil covers less lubricant than the edge area. At the end of the coil the measured values of the lubricant quantity reach the limit of the lower lubricant specification ( $l_{spec,min} = 0.80 \text{ g/m}^2$ ), whereas they exceed the upper lubricant specification limit of  $l_{spec,max} = 1.10 \text{ g/m}^2$ . The mean lubricant values per 250 m across the coil width lie between  $l_{mean,min} = 0.77 \text{ g/m}^2$  and  $l_{mean,max} = 0.85 \text{ g/m}^2$ . The determined range of average minima and maxima values is  $l_{total,min} = 0.47 \text{ g/m}^2$  and  $l_{total,max} = 1.29 \text{ g/m}^2$ . The effect of inhomogeneous lubricant distribution can be explained by the fact that the highest sheet thickness is located in the middle of the coil in coil width direction, due to the deflection of the rolls during the rolling process, as mentioned previously. This leads to higher contact pressures in that area which implicates a lubricant redistribution. Furthermore, one reason for the increasing redistribution over the coil length might be that the contact pressure and thus the displacement of the lubricant into the edge areas increases from the outer windings of the coil in the direction of the inner windings the so called coil eye, due to a decreasing diameter of the coil.

As shown before, coils may have different characteristics of lubricant distribution. Therefore, coils from one annealing date have been analyzed to gain information about the reason for the lubricant redistribution. The annealing date has been chosen as a reference to calculate the time span until the cutting process, since the impact of the storage time is one

**Fig. 9** Comparison of lubricant amount and distribution of the top and the bottom side of two coils; homogenous lubricant distribution (a) and inhomogeneous lubricant distribution (b)



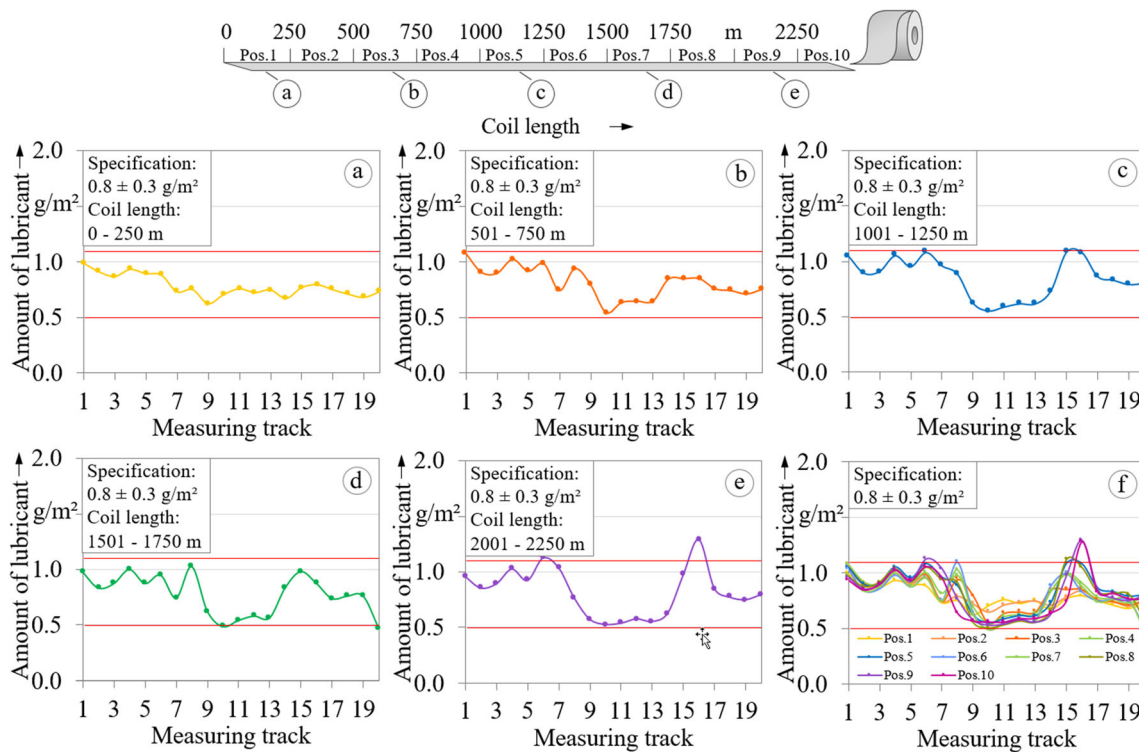


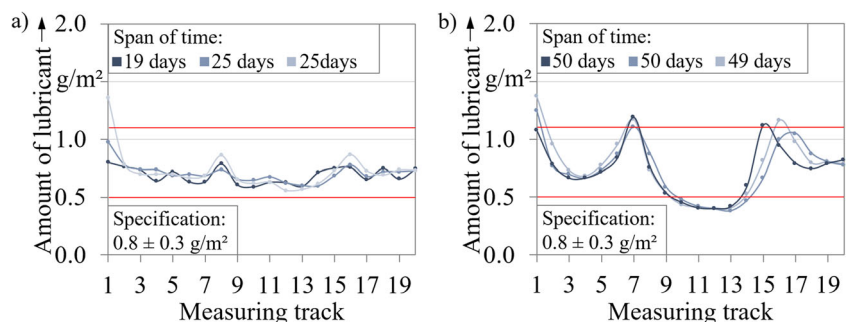
Fig. 10 Lubricant distribution over coil width at different positions over the coil length

assumed factor. In Fig. 11a) the averaged lubricant values per measuring track are plotted over the coil width for three coils annealed at the beginning of May 2019, which have been cut at the coil line 19 to 25 days after the annealing. All of them show a similar characteristic of lubricant distribution. The amount of lubricant reveals a homogeneous distribution within the tolerance limits of  $0.80 \pm 0.30 \text{ g/m}^2$ . Slight lubricant quantity peaks can be seen at track 8 and track 16. In addition, Fig. 11b) illustrates again three coils from one annealing date at the end of May 2019, which demonstrates also a similar characteristic to each other and have been processed at approx. 50 days at the coil line. In this case, the lubricant distribution over the coil width show a significant redistribution, where the amount of lubricant exceed the upper as well as the lower lubricant specification limits. Again, the greatest redistribution is at track 7 and track 15 and thus at similar positions compared to the coil shown in Fig. 11a). Hence, it can be seen that

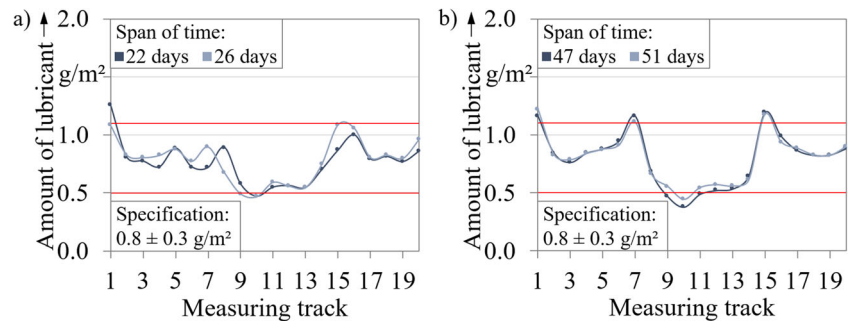
coils from the same cast, processed at the coil line in a similar time range have the same lubricant distribution characteristic over the coil width. Consequently, the appearance and characteristic of batch fluctuations regarding the distribution of the amount of lubricant can be clustered.

For confirmation of the effect of the storage time, coils from one annealing date processed at different dates have been compared. Figure 12a) shows two of the four coils processed after 22 respectively 26 days. It can be seen that the lubricant is not homogeneously distributed over the coil width. The mean values in the middle of the coil lie under the given mean values, whereas the mean values in the edge areas are close to the given mean value or slightly over it. Compared to these two coils Fig. 12b) shows two coils from the same annealing date, processed after 47 respectively 51 days. Due to the longer storage time the lubricant shows a very pronounced redistribution, with the result that the mean values in the middle of

Fig. 11 Comparison of the lubricant distribution over the coil width of three coils of one annealing date each processed at the coil line after approx. 25 days (a) or 50 days (b)



**Fig. 12** Comparison of the lubricant distribution characteristics over the coil width of four coils of one annealing date after less than 26 days (a) or more than 47 days (b)



the coil and at measuring track 7 and measuring track 15 exceed the given specification. By comparing the coils shown in Fig. 11a) with those of Fig. 12a) huge differences of the lubricant distribution can be determined. Although all 5 coils were processed within 26 days, some showed a homogeneous lubricant distribution and others a clear redistribution. Hence, a certain redistribution occurs shortly after the lubricant has been applied, whereas a longer storage time increases the redistribution effect. In this case, again the contact pressure, owing to the crowning of the sheet, can be assumed as one reason for the redistribution. Due to the fact that a preferably even coil thickness across the coil width is sought, which means that the crowning is as minimal as possible, the flowing of the lubricant into the edge areas is to be expected a continuously proceeding process. Thus, a longer time span between the annealing and the blank cutting process, leads to a more distinct lubricant redistribution. Consequently, the storage time has a significant impact on the lubricant redistribution. The investigations so far have shown that the amount of lubricant has a significant impact on the friction behavior in context of the given roughness and lubrication specification for the series production of car body parts. Thus, the amount of lubricant is identified as the key parameter. Furthermore, the analysis of the lubrication condition is carried out on the basis of a large amount of coil data, which has shown that the lubrication distribution changes in coil length direction as well as over the coil width and in addition changes as a function of time. The impact of fluctuating tribological conditions and thus fluctuating friction conditions will be analyzed by means of the FE-simulation.

## Results of the FE-simulation

So far, the standard simulation of car body parts has been carried out by using one friction coefficient which is assumed for the entire blank. However, fluctuating friction conditions are not considered until now. Thus, the aim of the following investigations using the FE-simulation is to understand the effect of varying tribological conditions on the forming result of car body parts. Consequently, the knowledge can be taken into account for designing the tools, which may increase the robustness of the process window. As a sample part the side

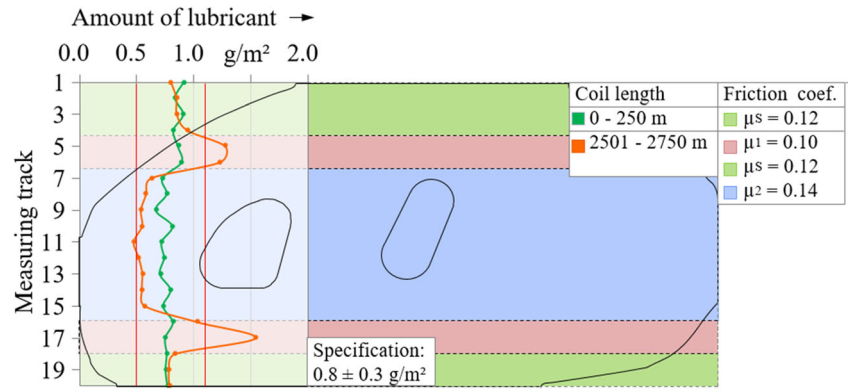
frame of the BMW X1 has been utilized for the simulation, for which the lubricant redistribution has been analyzed. For this purpose the already existing simulation model of this car body part has been used. In order to eliminate possible differences between the simulation model and the real car body part, due to tool changes, the radii have been remeasured in a first step. Furthermore, the material draw-in behavior of an actual drawing part has been matched with that in the simulation to validate the model. Thus, the model has been adapted so that the deviation of the material draw-in between the simulation part and the real part is smaller than 10 mm and can be assumed as sufficiently exact as described previously.

The following investigations have been carried out on the bases of production data of a production order in which cracks occurred. In a first step, the lubricant distribution of the coil has been analyzed based on inline measuring results. In a further step, in order to analyze the impact of varying friction conditions on the forming result the previously found effects of varying lubricant distributions across the coil width and length have been used to apply different tribological conditions to the blank in the FE-simulation.

The lubricant specification for this car body part is  $l_{\text{spec}} = 0.80 \pm 0.30$  g/m<sup>2</sup>. Furthermore, the material used is a deep-drawing steel CR3 with a surface roughness of  $Ra_{\text{spec}} = 1.10\text{--}1.60$  μm. Figure 13 shows the lubricant distribution over the coil width averaged over the first 250 m and in addition over the coil length range 2501–2750 m, on the left-hand side. At the beginning of the coil the amount of lubricant is distributed homogeneously. Towards the end of the coil the lubricant distribution show a significant fluctuation. In the area of track 5 and track 17 the amount of lubricant lie above the lubricant specification of  $l_{\text{spec}} = 0.80 \pm 0.30$  g/m<sup>2</sup>. Furthermore, the amount of lubricant between track 6 and track 16 lies close to the lower specification limit at approx. 0.50 g/m<sup>2</sup>. The lubricant amount in the edge area is within the intended range and lies around 0.80 g/m<sup>2</sup>.

Derived from the results of the previously performed strip drawing tests friction coefficients have been assumed for different areas of the blank, see Fig. 13 right-hand side. For areas where the lubricant quantity is 0.80 g/m<sup>2</sup>, a friction coefficient of  $\mu_s = 0.12$  is used. Areas where the lubricant quantity differs from 0.80 g/m<sup>2</sup> friction coefficients are assumed depending on

**Fig. 13** Illustration of the lubricant redistribution over the coil width determined at two positions in the coil length direction and the derived friction coefficients derived assigned to the side frame blank

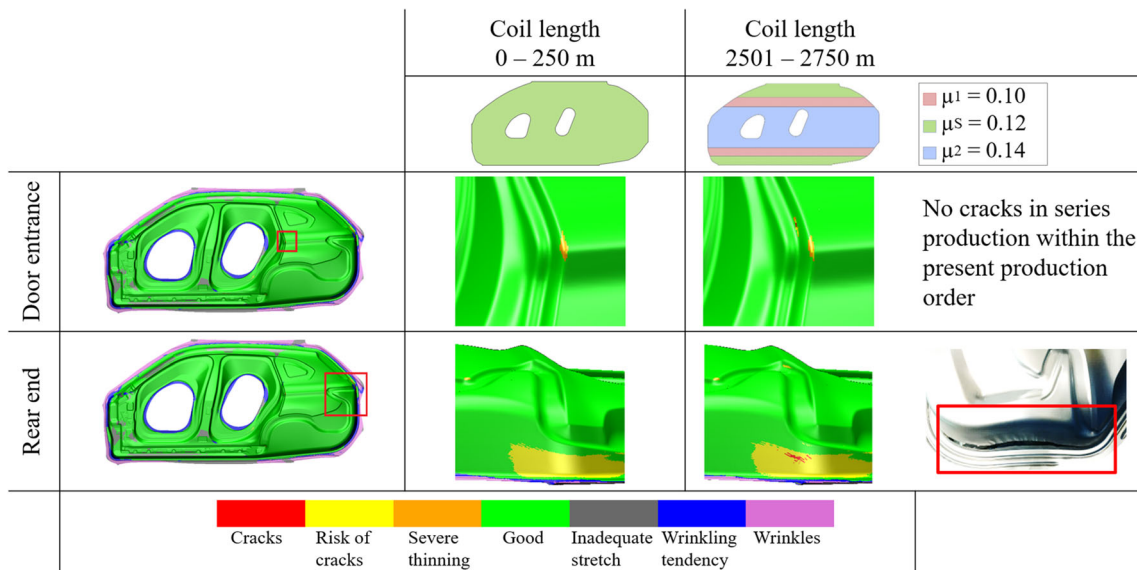


the varying amounts of lubricant. Hence, a friction coefficient of  $\mu_1 = 0.10$  is utilized in areas where the lubricant quantities exceed  $1.00 \text{ g/m}^2$ . Furthermore, a friction coefficient of  $\mu_2 = 0.14$  is used in areas showing low amounts of lubricant.

Figure 14 presents the simulation results. The calculation of the part using the standard friction coefficient of  $\mu_s = 0.12$  for the entire blank shows that a slight thinning and a risk of cracks may occur at critical areas of the part. Compared to this the simulation result of the part calculated with inhomogeneous friction conditions over the coil width shows that actual cracks are to be expected in critical areas. As a result, the lubricant redistribution over the coil width leads to areas where inadequate friction is present and thus cracks occur. In this case the simulation result shows that cracks occur at the back door entrance at the level of the character line and in addition at the rear end of the drawing part. In the present example of a real series production order cracks appear verifiably on actual car body part, where fluctuating tribological conditions are present. In this case the cracks only occur in the area of the rear end of the drawing part. Thus, the previously assumed homogenous friction

conditions are too optimistic compared to the shown simulation results of inhomogeneous friction condition over the coil width. The simulation result has shown that the batch fluctuations occurring in the series production have an effect on the frictional behavior so that the component quality is affected. In the present case, the effect is reflected in the simulation result, as well as on the real car body part by the occurrence of cracks. Thus, the investigation reveals that the simplified assumption of one friction coefficient for the entire blank in the simulation is too inaccurate.

The beforehand shown comparison of the part quality in the simulation and the real car body part has revealed the occurrence of cracks in rear end of the car but not at the door entrance. In a further production order of the opposite side frame, the lubricant distribution show a similar appearance than the one shown before as shown in Fig. 15a). In particular at the inner area of the coil from track 7 until track 14 the amount of lubricant is between  $0.42 \text{ g/m}^2$  and  $0.59 \text{ g/m}^2$  and thus fluctuates close to the lower specification of  $0.50 \text{ g/m}^2$  lubricant. In this case, cracks occurred at the door entrance but not at the rear end of the part, see



**Fig. 14** Comparison of the simulation results under homogeneous friction (Coil length 0 – 250 m) conditions and inhomogeneous friction conditions (Coil length 2501 – 2750 m) over the coil width

**Fig. 15** Lubricant distribution over coil width (a) and position of crack at the door entrance of side frame (b)

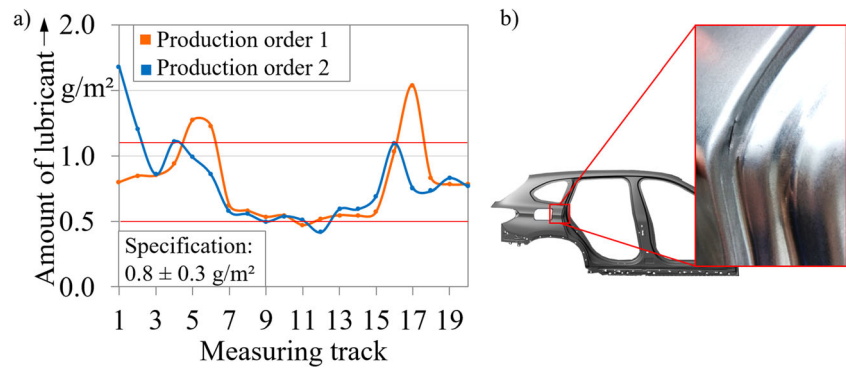


Fig. 15b). Consequently, the investigation reveals that fluctuating tribological conditions lead to a higher risk of cracks in the critical part areas although the actual position cannot be predicted. A further reason for divergent results between experimental investigations and the effects in series production of car body parts could be that further influencing variables cannot yet be taken into account or are still under investigation. These include, for example, the accumulation of lubricant in the forming tool, i.e. in the draw-beads, which influences the friction behavior. In addition, simplified assumptions have been made in this thesis by using flat strip drawing tests and merely considering material-side variations. An added value could be achieved by investigating the friction conditions performing draw-bead strip drawing tests, in order to take into account the friction conditions and contact conditions in the draw-beads. Furthermore, it is possible to influence the friction behavior manually by removing lubricant from the tool or on the other hand applying additional lubricant on the blank in the press line.

The investigations have shown that the amount of lubricant in comparison to the roughness has a significant impact on the friction behavior in series production of car body parts and is identified as the decisive tribological material parameter. The analysis of a large amount of data reveal that fluctuations regarding lubricant distribution occur depending on the time between the oiling of the coil and the cutting to length into blanks. Furthermore, the simulation displays the impact of varying tribological conditions on the car body part by considering the beforehand investigated batch fluctuations, which is confirmed by the quality of the series part.

Thus, on the basis of the presented investigations, a method has been developed, which makes it possible to determine actual occurring batch fluctuations with regard to the tribological properties, to consider these in the forming simulation and consequently improve the tool design. It can be stated that the forming result of car body parts is influenced by batch fluctuations regarding the tribological properties of the blanks. Quality problems as a result of inhomogeneous friction conditions are the consequence. The introduced method reveals, that actual batch fluctuations can be displayed in the forming simulation.

Considering batch fluctuations by assigning the present inhomogeneous friction conditions to the respective areas of the blank leads to an improved prediction accuracy of the forming result. In order to gain a robust production process of car body parts, which is less susceptible to batch fluctuations, the actual fluctuations occurring in the series process must be taken into account when designing the tools. Hence, the development of a robust tool design therefore leads to less scrap and an optimal utilization of the process window. The method presented is universally valid and can be transferred to other car body parts and other lubricant-surface combinations.

## Summary

One reason for cracks and waviness in series production of car body parts are batch fluctuations. So far fluctuating material properties, in particular fluctuating tribological conditions are not yet entirely understood and thus not considered in the forming simulation and respectively the tool design. Thus, within the present contribution, a method was introduced to take batch fluctuations into account in the simulation. The presented results of the experimental investigation have shown that the amount of lubricant in opposition to the sheet roughness has a significant influence on the friction behavior in sheet metal forming of car body parts in series production. Furthermore, the distribution of the amount of lubricant changes over the coil width and in coil length direction, which results in inhomogeneous friction conditions of the blanks. Furthermore, it was shown that the prediction accuracy of the part was enhanced by considering these fluctuations within the FE-simulation, which has been proven in series production of car body parts. In conclusion, the method presented offers the potential to consider the in series production existing tribological conditions and further to design tools more robust against batch fluctuations. Consequently, the occurrence of quality problems can be reduced and thus the productivity increased.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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