Modeling and control of tribological properties for subsequent forming process in skin-pass rolling

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Abstract. The surface roughness including average roughness (Ra) and peak number (RPc) after skin-pass rolling influences the strip's product properties, such as its friction coefficient in the subsequent sheet metal forming process. In order to both ensure an optimal tribological behavior and fulfill the process requirements of the following forming steps, predefined roughness combinations of Ra and RPc should be attained in skin-pass rolling. In this work, a preliminary friction model relating friction and combination of Ra and RPc is determined using flat die drawing tests for DC04 steel. The model is validated by deep drawing tests and embedded in a roughness control system for skin-pass rolling. To show a proof of concept for independent control of tribological properties from strip thickness, a simulation framework is implemented in Matlab/Simulink. The results indicate that the friction coefficient can be controlled between 0.0924 and 0.1003 for the considered test scenario (which is) characterized by a normal pressure of 75kN and a relative speed of 10mm/s.

Introduction and State of the Art

In modern industry, skin-pass rolling is used to adjust the strip's surface roughness by imprinting the work rolls' textured surface. Since skin-pass rolling is mostly the last rolling pass after conventional cold rolling, it influences the subsequent processes decisively by controlling the strip's surface quality. In accordance, correlations between the strip's roughness including average roughness (Ra) and peak number (RPc), and its tribological properties, i.e the friction coefficient, have been reported [1]. In sheet metal forming processes like deep drawing, friction is usually required to generate the necessary forming force and control the movement of the sheet within the dies [2]. At the same time, the friction coefficient significantly affects the springback, failure, minimal sheet thickness as well as the deviation of sheet thickness of the workpiece [3,4]. Under defined lubrication and deformation conditions, the sheet formability and cracking tendency also largely depends on the surface finish [5]. Hence, in skin-pass rolling a certain surface roughness shall be achieved in accordance with the subsequent forming condition for optimal tribological behavior to fulfill process requirements and avoid forming defects in the next process.

The friction coefficient primarily depends on the surface roughness, relative speed, normal pressure, and lubrication between the contact surfaces [2]. A common model is given by the Stribeck curve, which relates dynamic viscosity of the lubricants, relative speed, and normal pressure [6]. Three lubrication regimes can be identified from the Stribeck curve: boundary, mixed, and hydrodynamic lubrication, as shown in Fig. 1 (left). In the first two lubrication regimes asperity contact exists while in the third lubrication regime asperity contact can be neglected. Thus, there is less wear regarding both contact surfaces for high Hersey numbers. It can also be observed that the friction coefficient is relatively higher in boundary lubrication and the initial stage of mixed lubrication. Noteworthy, there is no clear boundary of the three lubrication regimes. Since in sheet metal forming the friction is required and avoiding the wear between sheet and tool is not the primary objective, only friction with limited amount of lubricant, i.e. boundary and mixed lubrication, is considered in this work.

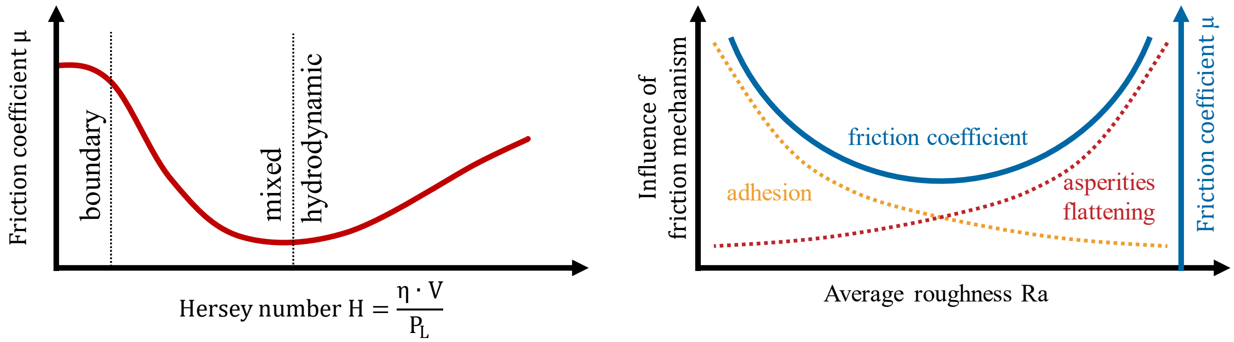


Fig. 1. Stribeck curve with the lubricant's dynamic viscosity η, relative speed V, and normal load per length PL (left); two mechanisms of influence of Ra on friction coefficient (right) [7] .

According to Stribeck curve the friction coefficient μ increases with lower relative speeds, higher normal pressures, and lower lubricant's viscosity in regions of boundary and mixed lubrication. However, some works [7,8] also show that a higher normal pressure causes lower friction in some pressure ranges and processes. The influence of surface roughness on friction has also been extensively studied in recent decades. Emmens et al. utilized flat die drawing tests and rotation friction tests to study the effect of surface roughness on friction for a deep drawing process with steel and aluminum [1,9]. Stribeck curves of specimens were determined for a surface roughness range from 0.1 µm to 3.08 µm. The result for steel indicates that a higher surface roughness regarding the maximal peak height (Rpm) causes a higher friction coefficient [1]. Here, the parameter Rpm is proportionally related to Ra. For aluminum the surface roughness shows a different influence on friction depending on the applied normal pressure. In case of lower normal pressure, the surface roughness has the same influence as for steel: higher Ra leads to a higher friction coefficient. However, when applying higher normal pressures, the friction coefficient drops slightly at first and then rises with a increasing Ra [9]. In another study, Zhou et al. investigated the influence of surface roughness on the friction coefficient by using a tribometer with a tool which moves reciprocally on the steel specimen surface[10]. The reciprocating frequencies were 2 Hz, 4 Hz, and 6 Hz and the specimen surface roughness (Ra) varied from 0.02 µm to 0.5 mm. The result reveals that below a testing frequency of 2 Hz a higher surface roughness causes a higher friction coefficient. For higher testing frequencies (4 and 6 Hz) the friction coefficient decreases at first and then increases again with increasing surface roughness. This non-linear behavior of the influence of roughness on friction coefficient (first decreasing and then increasing) is also observed by Lee [11] in flat die drawing tests and by Wihlborg [12] in bending under tension tests. This phenomenon can be explained as the interaction of two mechanisms, i.e., the adhesion between contacting asperities and the flattening of asperities, cf. Fig. 1 (right) [7]. With relatively lower surface roughness, the adhesion effect dominates while increasing roughness reduces the real area of contact and offers more lubricant pockets, therefore, friction coefficient decreases. With relatively higher surface roughness, the flattening effect dominates and asperities tend to be flattened by the normal load during the contact, which introduces more resistance for slide, and thus results in higher friction coefficient [7,13]. Because the decoupling of Ra and RPc is difficult in most roughening processes such as normal skin-pass rolling, shot-blast texturing (SBT), or electric discharged texturing (EDT), there is only limited amount of works focusing on the influence of RPc on friction coefficient. In fact, both positive and negative correlations between RPc and the friction coefficient can be observed under different test conditions [14,15]. According to the aforementioned works, the effect of surface roughness on friction depends on test types, and multitude of different processes and lubrication conditions in different ranges of roughness. Due to this complexity, the type of friction test and its condition should be chosen carefully in accordance with the considered forming process.

In order to produce strips with a defined surface roughness in skin-pass rolling, the surface roughness of work rolls or the transfer ratio during imprinting should be adjusted. Because of the time and cost inefficiency of producing and changing rolls with different surface roughness, frequent change of work rolls should be avoided. Therefore, the adjustment of strip's surface roughness is usually achieved by changing the roughness transfer ratio, which is influenced by several process parameters. Kijima et al. [16,17] found that the peak pressure within the roll gap and work roll radius influence the roughness transfer ratio: Higher rolling forces lead to better roughness transfer as the peak pressure in the roll gap is higher, and a greater roll radius is favorable for roughness transfer due to higher peak pressure. The work of Çolak et al. [18] shows that in dry and lubricated condition higher rolling speeds and higher thickness reductions increase the rolling force and thus the transfer ratio. Furthermore, according to industrial practice lower strip tension in skin-pass rolling causes higher imprinting [19]. This effect was also investigated in preliminary work by Li et al. [20] and validated using multi-scale finite element (FE) simulations. Along with a higher thickness reduction, decreased strip tension causes higher average roll pressure and consequently increases the transfer ratio. The potential of changing the strip's surface roughness by varying strip tension was indicated in this work as well. The aforementioned process parameters, especially thickness reduction and strip tension, can be employed during skin-pass rolling for controlling the transfer ratio and adjusting the product's surface roughness, thus enabling automatic control.

Conventionally, a tandem rolling mill is used to control strip roughness during skin-pass rolling. It uses an allocation of the total height reduction between the two rolling stands to independently control the strip roughness from the strip thickness. Li et al. [21] used a tandem rolling mill together with a heuristic model to control the resulting strip roughness. The heuristic model employed here describes the correlation between the tactile measurement of the strip roughness with the process force, roll roughness, and roll radius. Overall, a roughness of (0.42 ± 0.05) µm could be ensured for 65 % of the material, in contrast to 15% in the uncontrolled case. The heuristic model of Bozhkov et al. [22] predicts the resulting strip roughness based on the average contact stress, roll radius and material strength. Here, experimental validation demonstrated that there was an average deviation between measured and predicted strip roughness of 7% with varying strip roughnesses between 1 µm and 2.5 µm over 170 km of strip.

Utilizing the strip tension to manipulate the imprinting represents an alternative method, first validated in [23]. The independent control of strip roughness and strip thickness with the use of strip tension has the advantage that no additional height reduction is necessary. However, it has the disadvantage that strip tensions of up to 40 % of the material yield strength are necessary to obtain a sufficiently large process window [23]. In preliminary work, the strip tension could be used together with the manipulation of the roll gap to vary the roughness of the strip by 0.3 µm with a height reduction of 5% and an initial strip thickness of 1 mm. However, due to the high measurement noise of the roughness measurement and the insufficiently high strip tension, this should only be considered as a proof-of-concept [23].

So far there is no publication on the process control of skin-pass rolling with regard to the strip's friction coefficient. As a preliminary trial, the task of this work is at first the determination of the friction coefficient of steel specimens with different surface roughness under test conditions, which resemble a subsequent deep drawing process. The result is utilized to model the influence of Ra and RPc on the friction coefficient. The second task is including this friction model into a control system for skin-pass rolling with roughness control to ensure production of strips with desired tribological properties that meet the requirements of the subsequent forming process. A Matlab simulation framework is implemented based on process models validated in previous work. In particular, a model for predicting the rolling force according to Bland & Ford (1948) [24], a function for modeling the progressive roll stand deflection [25], and a heuristic function describing the imprinting of the rough work rolls are used [23]. Moreover, using the strip tension and tandem rolling as actuators, the two aforementioned concepts for roughness control in skin-pass rolling are combined in order to obtain the largest possible variation range of roughness and friction coefficient. A typical rolling test is presented in which the desired tribological property is varied while keeping a constant strip geometry.

Materials and Flat Die Drawing Test

In this study two steels, DC01 and DC04 are used. DC04 is primarily considered in the friction model and the considered deep drawing process. However, our DC04 strip is too narrow for the flat die drawing machine, and the amount of the wider DC04 plates we have is limited. Due to this geometric restriction, a similar material, DC01 is applied in friction tests. The result is compared to some additional friction tests with DC04 plate specimens to ensure the substitutability of DC01 for DC04 results.

The surface of test strips is treated by SBT to create different surface roughness. Roller leveling is used afterwards to ensure the flatness of specimens. The surface roughness Ra and RPc were measured using a mobile roughness measuring tool MarSurf PS1 by Mahr GmbH in accordance with DIN 4287. The Ra and RPc of the specimens are listed in Table 1. Note that #1 is not treated by SBT and as a result, shows both the lowest Ra and RPc values while in other specimens (#2 to #5) RPc decreases with a higher Ra.

Table 1. Specimens and parameters used in flat die drawing test.

Specimen	Material	Geometry [mm^3]	Ra [µm]	RPc [1/cm]	Normal pressure P [MPa]	Drawing speed V [mm/s]
#1			1.02	66		
#2			1.55	171		10
#3	DC01	1*10*1000	2.14	146	10, 25, 50, 75	
#4			2.96	125		
#5			3.46	105		5, 10, 50
#1-V #3-V	DC04	1*32*1000	1.04 2.03	72 152	50	10

As illustrated in Fig. 2, the friction parameter is determined using flat die drawing test with Tribometer 5000 by Raziol Zibulla & Sohn GmbH. The tool with a size of 200mm2 is made of steel 1.2379 with hardness of HRC 63. The DC01 specimens are tested with normal pressures of 10MPa, 25MPa, 50MPa, and 75MPa with a drawing speed of 10 mm/s to determine the influence of Ra, RPc, and normal pressure, see Table 1. For specimen #5 extra tests with varied drawing speeds of 5mm/s and 50mm/s are conducted to investigate according correlations. The tests with DC04 specimens (#1-V and #3-V) with a normal pressure of 50MPa and a drawing speed of 10mm/s are used as a comparison to the respective tests with DC01 (#1 and #3) to ensure that the result of DC01 can be generalized for DC04. The lubricant WISURA LS 710 by Fuchs Lubricants

Germany GmbH is applied while the lubrication condition for all tests in this work is controlled using a laboratory lubrication system by Raziol Zibulla & Sohn GmbH with a nozzle opening value of 35, nozzle height of 35mm, and oil pressure of 3 bar. Every test is repeated 4 times with fresh specimen. The results are then averaged for the subsequent analysis.

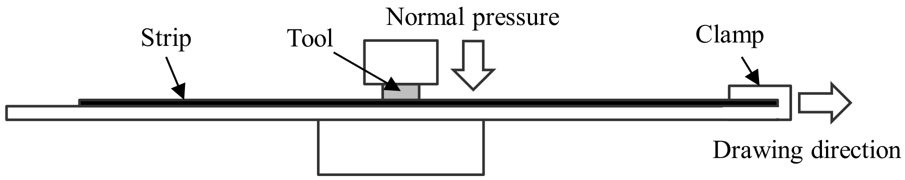


Fig. 2. Flat die drawing test.

The result of flat die drawing test for DC01 is depicted in Fig. 3. The influence of normal pressure P can be observed in Fig. 3 (left): Under this test condition a higher normal pressure causes a lower friction coefficient, which is also noticed in other works [7,8]. Because of the totally different Ra and RPc combinations of specimens the influences of Ra and RPc on friction coefficient are difficult to separate from each other, see Fig. 3 (middle, right). However, it can still be noticed that a descending tendency exists with higher Ra and lower RPc, if #1 is neglected due to the irregularity of its Ra and RPc combination. This influence of Ra can be explained with the domination of the adhesion mechanism: higher Ra decreases the real contact area, and thus, the friction coefficient [7,13]. Moreover, higher RPc results in narrower peaks and valleys on the contact surface, which then deforms easier due to the flattening effect [7]. Accordingly, the real contact area increases, the volume of lubricant pockets decreases and consequently higher friction coefficients result. It is also visible that the effect of Ra and RPc is more obvious with higher normal pressures: The maximal difference of friction coefficient at a normal pressure of 10 MPa is 0.0106, while the maximal difference of friction coefficient with a normal pressure of 75 MPa is 0.0231. This result of flat die drawing test is also plotted in 3D space, see Fig. 4 (left). Here, the different combinations of Ra and RPc of the specimens can be clearly identified.

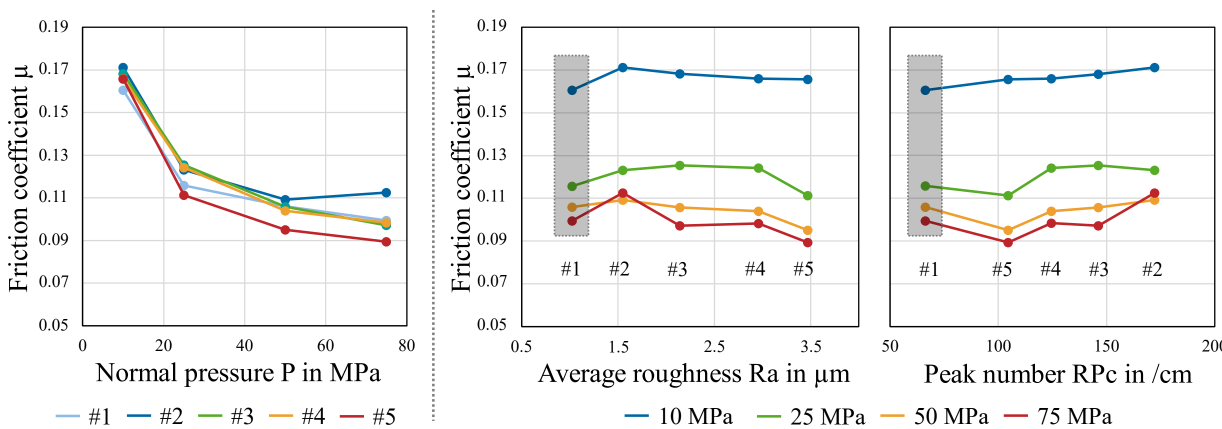
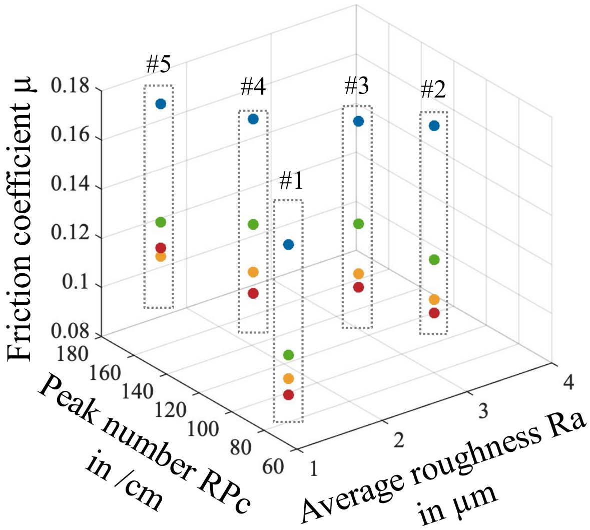


Fig. 3. Results of flat die drawing tests for DC01. The evolution of friction coefficient is illustrated over normal pressure P (left), average roughness Ra (middle), and peak number RPc (right).

Drawing speed is varied for test series #5 while a normal pressure of 50 MPa is applied. Fig. 4 (right) shows the minor influence of the drawing speed on friction under this test condition: Higher relative speeds lead to slightly lower friction coefficients, which is also observed in the Stribeck curve.



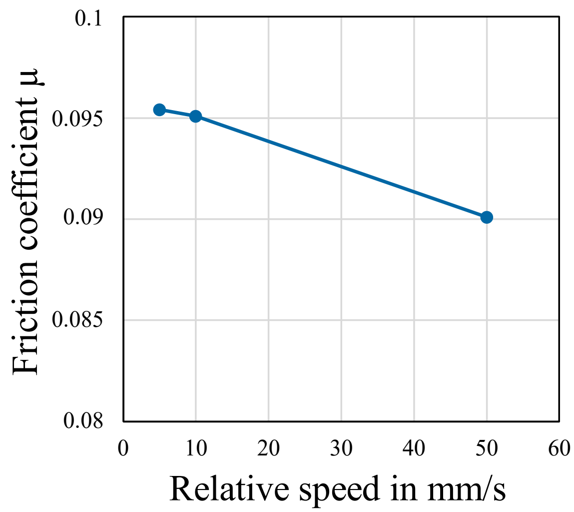


Fig. 4. Result of flat die drawing test for DC01 in 3D space (left); Influence of relative speed on friction coefficient (right).

Comparing the friction coefficients derived for DC04 and DC01, only small deviations are apparent, see Table 2. This result can also be supported by the similarity of the two steels' chemical compositions and mechanical properties. Therefore, the results obtained for DC01 can also be generalized for DC04, given the same test conditions.

Table 2. Comparison of the results of DC04 and DC01.

Specimen	Normal pressure P [MPa]	Drawing speed V [mm/s]	Friction coefficient μ[-]		Deviation [%]
			DC04	DC01	
#1-V (DC04) and #1 (DC01)	50	10	0.1058	0.1060	- 0.19
#3-V (DC04) and #3 (DC01)			0.1067	0.1057	0.95

Modeling of the Friction Coefficient

Based on the results of the flat strip drawing tests, a preliminary friction model considering the influence of normal pressure P, average roughness Ra, peak number RPc, and relative speed V is fitted using flat surfaces for different normal stresses, as shown in Fig. 5 (left). Accordingly, the friction coefficient μ is calculated as:

$$\mu = f(\mathrm{Ra}, \mathrm{RPc}, \mathrm{P}, \mathrm{V}) = (\mathrm{a} + \mathrm{b} * \mathrm{Ra} + \mathrm{c} * \mathrm{RPc}) * \mathrm{d} \tag{1}$$

where [b]= /μm and [c]=cm, and a and d are dimensionless. These fitting parameters a, b, c, and d mapping the normal pressure, Ra, RPc, and relative speed respectively. These fitting parameters are given by:

$$a = 1.987 * P^{-1.549} + 0.09679 \tag{2}$$

$$b = -0.0003376 * P^{0.763} + 0.001973 \tag{3}$$

$$c = 4.426 * 10^{-5} * P^3 - 5.358 * 10^{-8} * P^2 + 1.751 * 10^{-6} * P + 9.141 * 10^{-5} \tag{4}$$

$$d = 1 - 0.001038 * (V - 10) \tag{5}$$

with [Ra]= µm, [RPc]=/cm, [P]=MPa and [V]=mm/s. As extrapolation strategy, parameters b and c are fixed if the normal pressure is outside the measured data, i.e., lower than 10MPa and higher than 75MPa.

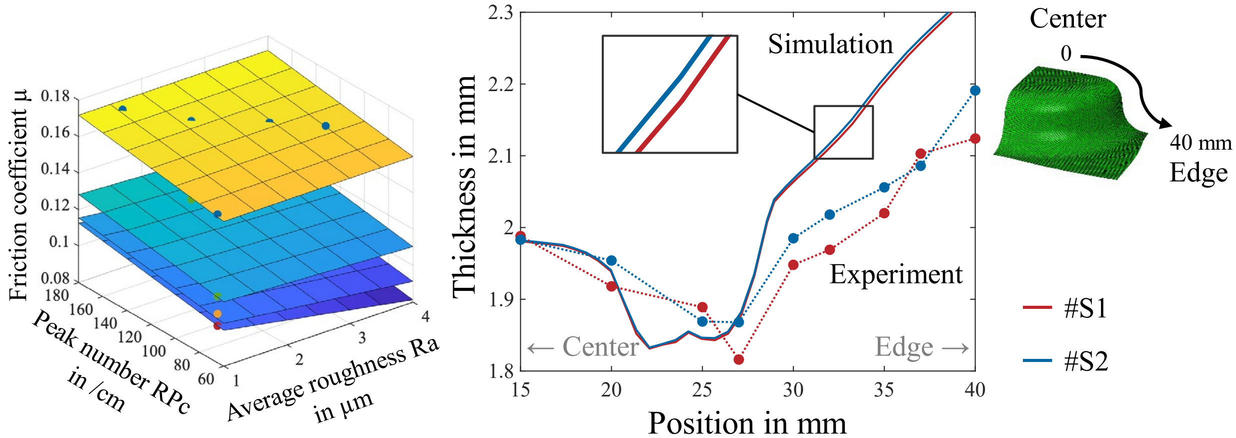


Fig. 5. Fitted friction model (left); Validation of the friction model (right).

With a maximal deviation of -5.77% the friction model shows a good agreement with the measured data and is sufficient to describe the friction behavior under the given conditions, see Table 3.

Table 3. Deviation of the fitted model from the measured data recorded at V = 10 mm/s.

Specimen	Deviation [%]			
	10 MPa	25 MPa	50 MPa	75 MPa
#1	-0.36	0.14	-5.43	-5.77
#2	0.04	2.68	2.99	3.62
#3	0.16	2.02	1.66	4.92
#4	1.57	4.13	1.86	3.78
#5	0.82	4.24	3.00	0.11

The friction model is also implemented in FE simulations using the user-subroutine FRIC_COEF with continuum shell elements in Abaqus/Standard 6.14. The results are validated with deep drawing (cupping) tests with tool speed of 5 mm/s, blankholder force of 60 kN, drawing depth of 15 mm, and punch diameter of 50 mm. As shown in Table 4 two DC04 plates with different surfaces are employed for validation. The corresponding experiment is conducted on a deep drawing press by Lauffer GmbH. After the experiment the thickness along the center line is measured using a thickness gauge by Mitutoyo with a precision of 0.01mm.

These measured thickness profiles are compared with the ones obtained from the simulation and presented in Fig. 5 (right). The results of simulation and experiment show the same tendency: from center to edge the thickness reduces at first, which is induced by large deformation in radial direction near the cup corner. Then the thickness increases significantly, which is caused by tangential material flow on the side and flange. On the edge of the specimens, the thickness of #S2 is higher than the thickness of #S1 due to the different initial surface roughnesses, which can also be observed in the simulation. The maximum relative deviations of #S1 and #S2 between simulation and experiment are 8.61% and 8.54%, respectively. This is due to the flattening of surface asperities on the edge, which is visible after the deep drawing experiments (see Fig. 6 left) and is not considered in the friction model. Another reason of this deviation is that the maximal normal stress in this deep drawing process is notably higher than for the flat die drawing tests.

Especially near the cup corner high normal stress is observed and it can cause poor extrapolation, cf. Fig. 6 (right). Moreover, the substitutability of the results of DC04 and DC01 can also be affected by the high normal stress. In addition, measurement errors stemming from the thickness gauge should also be considered.

Table 4. Specimens for deep drawing tests with their initial roughness.

Specimen	Material	Geometry [mm^3]	Ra [µm]	RPc [/cm]
#S1	DC04	2*80*80	2.92	130
#S2			4.44	99

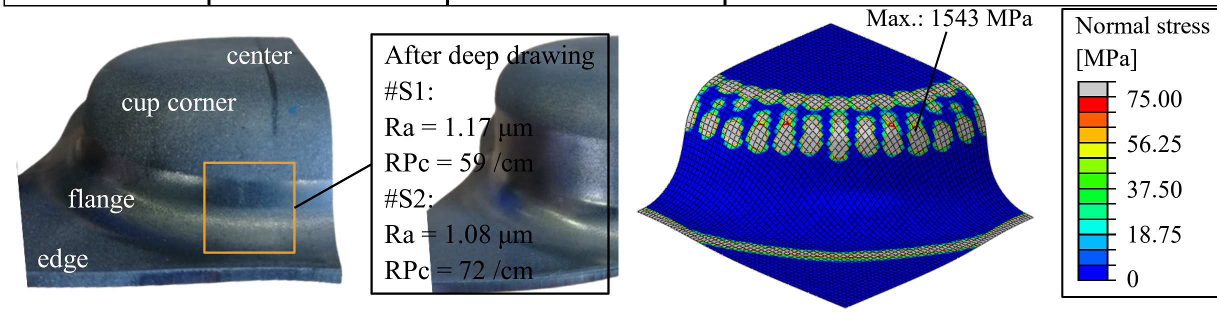


Fig. 6. Flattening of surface asperities after experiments (left); normal stress distribution in deep drawing (right).

Automatic Control of the Friction Coefficient

To show a proof of concept for independent control of tribological properties and strip thickness, a simulation framework is implemented in Matlab/Simulink. A tandem rolling mill with a quarto rolling stand with flat work rolls and a duo rolling stand with EDT work rolls with a Ra of 3 µm and RPc of 78 1/cm are modeled. In order to enlarge the process window, the control system is combining the roll gap actuation of a tandem rolling mill with the strip tension in the incoming and outgoing strip t_0 and t_2, respectively. The strip tension between the stands t_1 is kept constant in order to avoid cross-coupling of the two roll gaps. In order to keep the number of manipulated variables small, the strip tension at the entrance was set equal to the strip tension at the exit. This simplification had no negative impact on the possible process window of the control, since both actuators share a positive correlation with the friction coefficient.

The presented friction model as well as a cold rolling, roll stand deflection and imprinting model from prior work are embedded into the model-based optimal control system with a sampling time of 5 ms and a rolling speed of 100 $\mathrm{m/s}$. The material under consideration is DC04 steel and a rolling speed of 50 m/min is selected, so that actuator speeds are well within in their respective admissible sets. Lubrication is neglected and the simulated process variables are superimposed by process and measurement noise according to a real tandem rolling mill from Bühler Redex GmbH with modified measurement setup [26]. The strip tension can be varied in the simulation between 150 N and 3000 N.

The simulative results are presented in Fig. 7. The actuator values are shown in the two lower diagrams. The roll gap heights of the two roll stands are shown at the bottom left and the strip tensions are shown at the bottom right. The diagram at the top left shows the initial strip thickness h_0, the strip thickness between the two roll stands h_1 and the strip thickness at the exit h_2 along its reference $h_{2,des}$. It can be seen that the outgoing strip thickness tracks the constant reference of 0.93 mm with minimal error (root mean squared error of 1.1 µm), despite of incoming strip thicknesses h_0 of (1 ± 0.008) mm, which reflects actual material tolerances present in DC04 steel. The measured and desired friction coefficient µ are shown in the diagram at the top right. Reference values between 0.093 and 0.101 are specified in 0.001 steps. The controller attains the

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desired friction coefficients μ with exception of coefficients over 0.1 which prove infeasible due to the constraints on the strip tension and the minimal contact requirement of the second roll stand.

The feasible process window (friction coefficient as a function of the selected strip thickness h_2) for an exemplary sheet metal forming process with a normal pressure of 75kN, relative speed of 10 mm/s, and controlled lubrication condition is shown in Fig.8. Here, the maximum and minimum adjustable friction coefficient are shown as two enveloping lines. By increasing the total height reduction, the maximum of the friction coefficient can be significantly increased. For a height reduction of 7%, a friction coefficient between 0.0924 and 0.1003 can be set in the demonstrated process, which corresponds to a variation of 8.6%. Extending the actuators' working range would also increase the feasible process window.

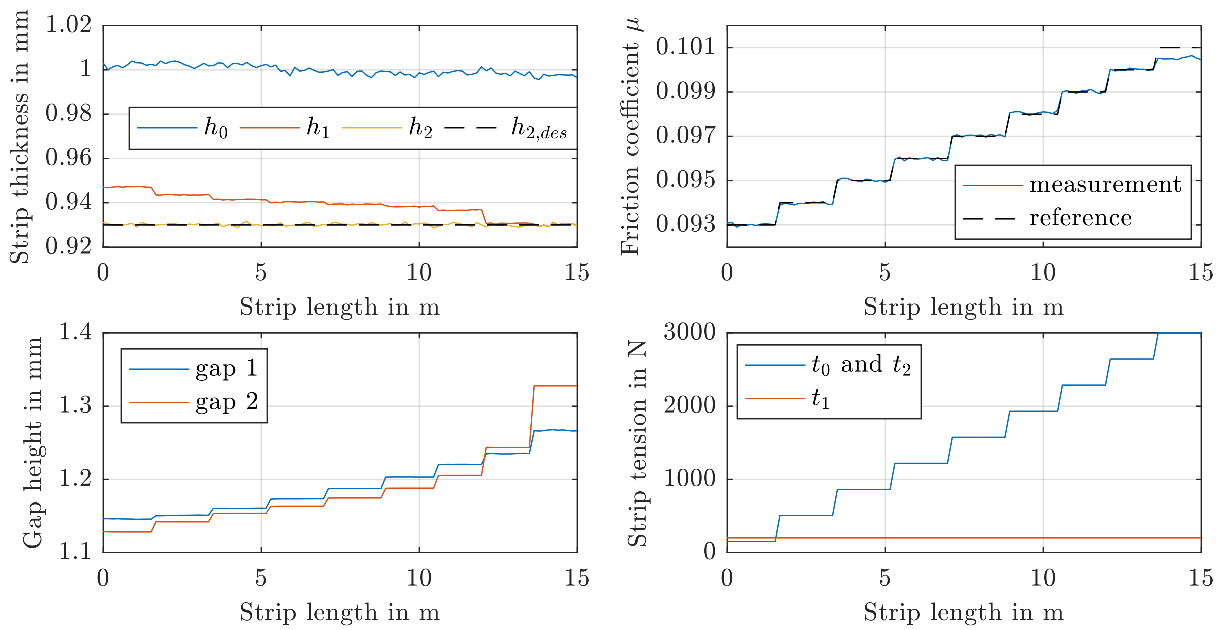

Fig. 7. Simulative results of independent control of strip thickness and friction coefficient μ.

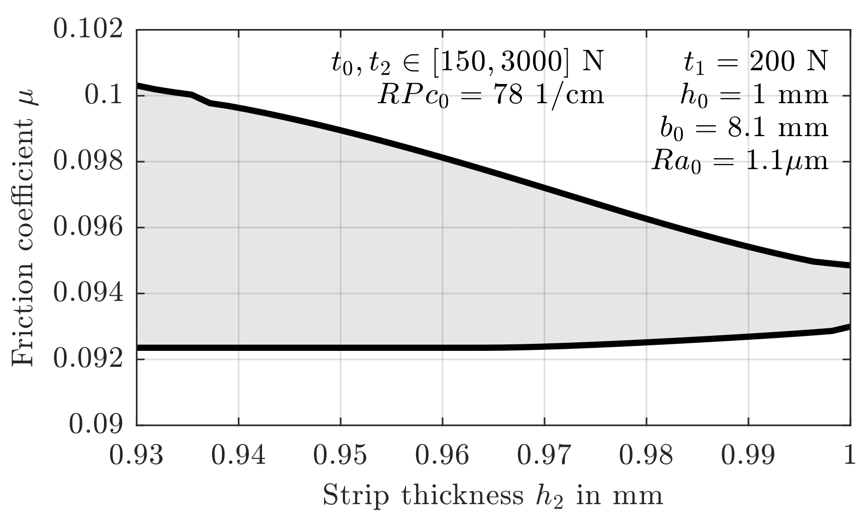

Fig. 8. Simulative evaluation of the realizable process window for DC04.

Summary

In this work, the influence of Ra and RPc on the friction coefficient of the considered deep drawing process is investigated in experiments and simulations. The results show that a higher Ra and lower RPc decrease the friction coefficient under the given conditions. Based on this result a preliminary friction model considering the influence of Ra, RPc, normal pressure, and relative speed is proposed. The model is validated qualitatively using deep drawing tests.

The friction model is embedded into a simulated control system for skin-pass rolling. The simulations suggest that the system is capable to control the surface roughness to optimize the tribological property of friction for the subsequent forming process while decoupling a predefined strip geometry

In future work, a more precise friction model should be determined by obtaining more measured data with higher normal stress and considering the asperity flattening during sheet metal forming. In addition, a validation of the simulation results should be performed to evaluate the transferability of the friction model derived from SBT surfaces to skin-pass rolling surfaces. Furthermore, the required roll surface per roll stand that extends the process window of control could be investigated, particularly with regard to the peak number.

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