

Advanced tribomechanical modelling of sheet metal forming for the automotive industry

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Abstract. Deep drawing is commonly applied in the automotive industry to produce high quality automotive panels. The deformations applied to the sheet metal in these processes are complex. Accurate modelling of the sheet metal behaviour and its interaction with the forming tools is crucial to quantitatively predict these forming processes. Thus, an accurate material constitutive model and an accurate tribological model are required. In this paper, the current state-of-the-art of sheet metal forming models are used to investigate the model predictions, i.e. the Tata Steel constitutive material model and the friction model implemented by TriboForm. A cross-die experiment on an uncoated automotive sheet steel is performed as a base of reference to assess the prediction quality. The strain evolution in the cross-die formed samples is compared to the numerically predicted evolution. The results show a dependency on the applied deformation mode and the accuracy of the numerical model on the accuracy of the predictions.

1. Introduction

Forming operations, e.g. deep drawing, are commonly applied in the automotive industry to produce high quality car body panels. During these operations, the metal sheet material is subjected to complex forming loads to reach the desired final shape. Typically, the material flow is controlled through an applied force on the blank holder, i.e. the blank holder force, and draw beads which restrain the flow. For the material, two contributions determine the material response to these constraints, i.e. the constitutive material behaviour and the tribological properties of the material. The material behaviour is determined by the mechanical properties of the sheet metal, while the tribological behaviour is determined by the used system, i.e. the selected tooling, lubricant and metal sheet surface properties. To meet the ever increasing demands on product quality, the industry faces the challenge to accurately predict the material flow during production to ensure consistent product quality. Thus, high quality predictions of the material flow is required.

The modelling of the material constitutive behaviour of sheet metal has received significant attention in the past, e.g. the models developed by Vegter et al. [1] and Abspoel et al. [2]. These models incorporate the material anisotropy [1], [3], work hardening [4], and the failure limits [2]. Furthermore, these models are easily accessible through commercial software for simulating forming processes [2], [5].

However, the modelling of the tribological behaviour has received far less attention. From literature it is known that the effect of friction becomes dominant over material plasticity effects if the contact area is increased, especially in the case of large automotive body panels [6]. The most commonly applied friction model is the Coulomb friction model, which assumes a constant coefficient of friction. However, the measured coefficient of friction is only applicable under the experimental conditions where it was



measured [7]. Clearly, during complex metal sheet forming processes, these experimental conditions are not constant and thus the applicability of the Coulomb friction model is limited. Some more advanced tribological models have been developed, which incorporate different parameter influences, e.g. the lubricant type and amount, the metal sheet surface roughness, the sliding velocity, the temperature and the strain rate.

In previous work, i.e. [8], [9], the accuracy of the Coulomb friction model, which used an optimised friction coefficient, and an advanced friction model, i.e. the model implementation of TriboForm in AutoForm^{plus} R6.0, was investigated. For the Coulomb model, the friction coefficient was calibrated to match the global experimental results. The results showed that the accuracy of the advanced model depends on the presence and type of a protective metallic coating on the sheet metal. For a Zinc-Magnesium coating, both the advanced friction model and the Coulomb model showed a comparable accuracy when compared to the experimental results. However, the accuracy for the advanced model was much less for a standard Zinc galvanized coating, indicating that this model does not accurately capture the influence of the coating on the friction coefficient.

In this work, the current state-of-the-art modelling is again applied to investigate the accuracy of these models in a cross-die deep drawing experiment. This experiment is designed to replicate the experimental conditions typically seen during automotive sheet forming. Here, the accuracy is investigated for an uncoated material, thus removing the influence of the galvanizing coating. The samples are drawn to different depths to study the evolution of the prediction accuracy.

2. Experimental

An uncoated low carbon steel grade was investigated in this work, i.e. a VDA239-CR4 material. The material properties are given in Table 1. The surface topography, which plays an important role in the resulting tribological properties, was measured using a confocal optical microscope and is shown in Figure 1(a).

Table 1. Thickness and material mechanical properties.

Grade (VDA239)	Gauge [mm]	Test direction	Rp [MPa]	Rm [MPa]	A80 [%]	n-value [-]	r-value [-]
CR4 UC	0.70	RD	161	308	43.6	0.22	2.03

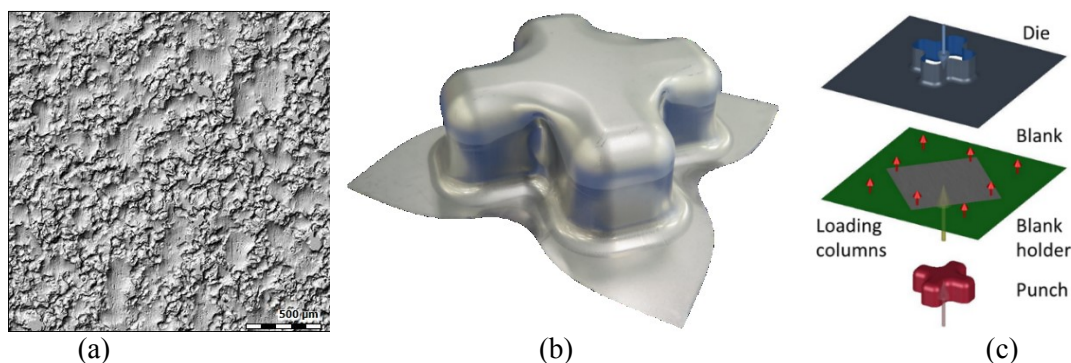


Figure 1. (a) Undeformed surface roughness profile; (b) the cross-die geometry; and (c) the computational model.

The tooling used in the cross-die deep-drawing experiments has a tool roughness of approx. $R_a = 0.2 \text{ } [\mu\text{m}]$. The experimental geometry is shown in Figure 1(b). The metal sheets were cut into square blanks of 260 [mm] width and cleaned in an alkaline soap bath, which was followed by re-applying the mill applied lubricant (36 [cSt] at 40 [°C]). The lubricant quantity was 1.0 [g.m⁻²], which was verified using a OFIS-3016 lubricant measurement device calibrated for the lubricant and sheet surface. The samples were drawn to different drawing depths to study the simulation accuracy for different depths. The blank holder force was set to be in the centre of the forming window for this material, i.e. 100 [kN]. The punch speed in all cases was 60 [mm.s⁻¹]. To compare the draw-in of the experiments and

simulations, the flange contour of the deformed samples was measured with a 3D coordinate measuring machine (CMM). Finally, some blanks were electrochemically etched to create a polka dot grid pattern before forming. After forming, these parts were used for full-field optical strain measurements.

3. Numerical accuracy assessment

The cross-die deep drawing test was modelled in AutoForm^{plus} R6.0 with the real dimensions and experimental tool geometry, see Figure 1(c). The blank holder force was modelled with eight vertical loading columns at locations similar to the experimental tooling. The constitutive material behaviour was modelled using the Vegter yield locus implemented in AutoForm^{plus} R6.0 with temperature and strain-rate dependent hardening. Details of material model generation is discussed in [5].

Two tribological models were used in this work. The first model used was the classical Coulomb friction model which uses a constant coefficient of friction. The friction coefficient was calibrated to accurately capture the experimentally observed draw-in of the sheet metal. This method was previously used in [8], [9]. The resulting optimised friction coefficient is $\mu = 0.162$. For the second model the TriboForm implementation in AutoForm^{plus} 6.0 was used. Dedicated friction experiments were performed on a rotational friction test to fit the model. The resulting model predicts the coefficient of friction as a function of the applied pressure, strain, temperature and sliding velocity.

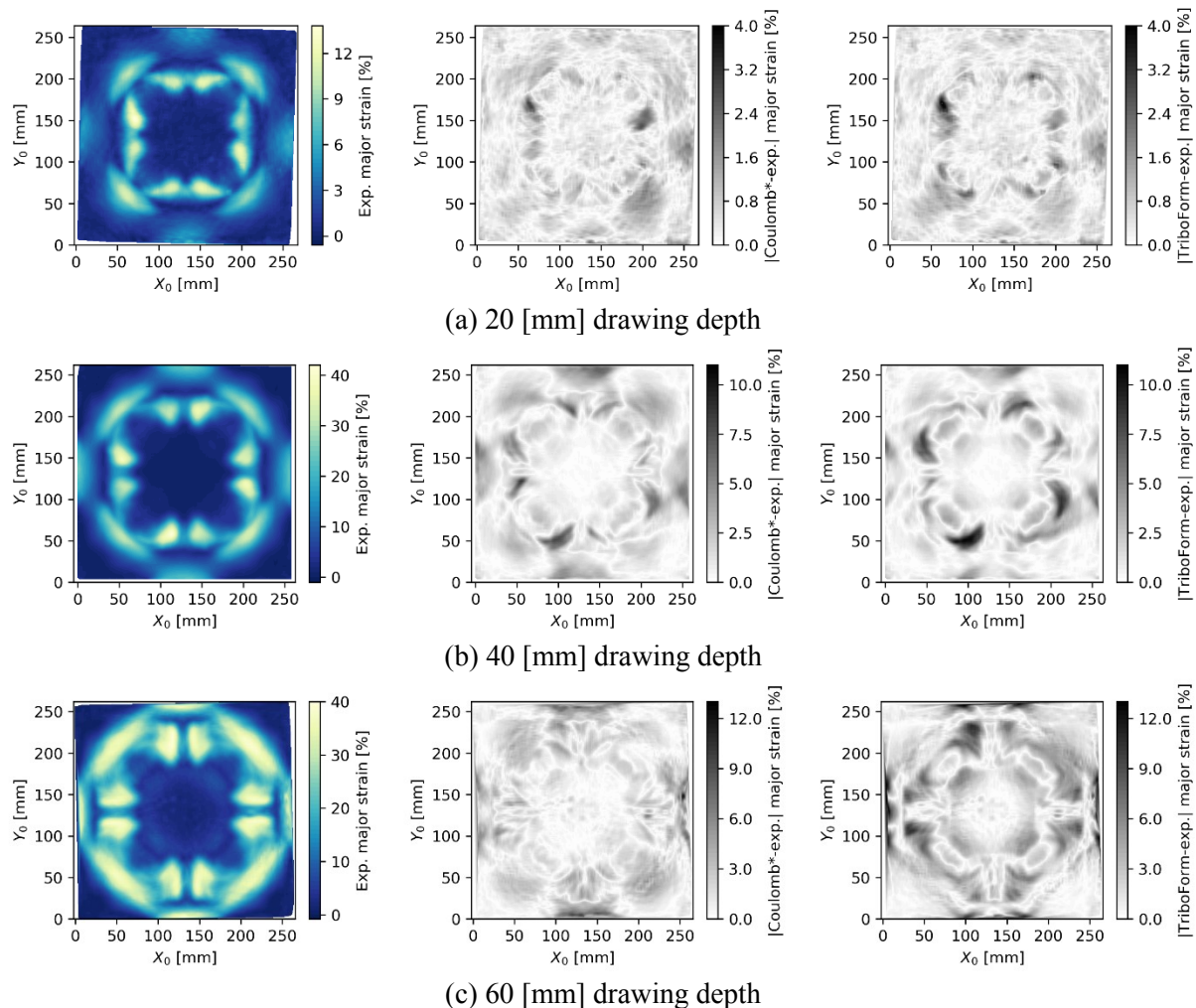


Figure 2. Comparison between the experimental major strain distribution and the strain predicted in the simulations using the different tribological models for the uncoated CR4 material; (left) experimental strain map mapped on the undeformed blank sheet; and the absolute differences between the experimental and simulated results for (centre) the Coulomb model and (right) the TriboForm model.

The predictions of the models are compared to the experimentally measured major and minor strains in the cross-die experiment. Figure 2 shows the experimentally measured major strain and the difference between the predictions of the two different models and the experiments for the different drawing depths. The strains are mapped to the undeformed configuration to allow for a two-dimensional comparison between the predictions and the measurements. The results for a drawing depth of 20 [mm] (Figure 2(a)) show that both models predict the major strains accurately. Some deviations in the predicted strains can be observed near the areas of high strain with a maximum of 4% strain deviation. For the drawing depth of 40 [mm] (Figure 2(b)), the differences between the predictions and the measurements are more pronounced. The results for the Coulomb model shows a smaller error compared to the results for the TriboForm model. These differences become more pronounced for a drawing depth of 60 [mm] (Figure 2(c)). Comparing the predictions for the minor strains, i.e. Figure 3, shows similar results. However, for the minor strains, it can be clearly observed that the predictions of the TriboForm model for the drawing depth of 60 [mm] (Figure 3(c)) predict a wrong minor strain in the area where the material flows into the corner areas of the cross-die, see the arrows in Figure 3(c, right).

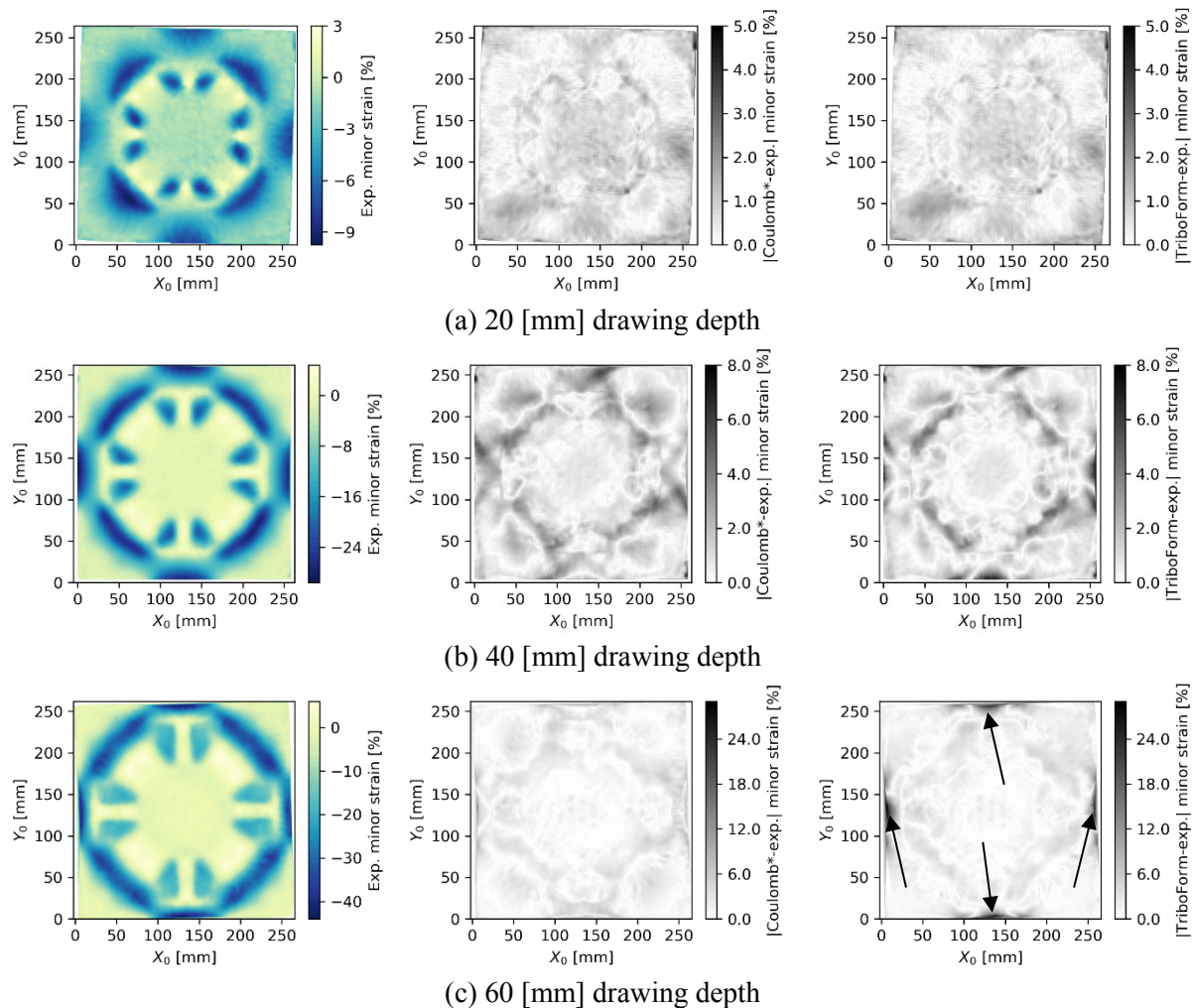


Figure 3. Comparison between the experimental minor strain distribution and the strain predicted in the simulations using the different tribological models for the uncoated CR4 material; (left) experimental strain map mapped on the undeformed blank sheet; and the absolute differences between the experimental and simulated results for (centre) the Coulomb model and (right) the TriboForm model. The arrows indicate the areas where material flows in to the corner areas of the cross-die.

Boxplots of the absolute differences between the major and minor strains predicted by the two models and the experimentally measured strains are shown in Figure 4. It can be seen that the mean error in the strains, both major and minor, grows with an increase in the drawing depth for both models. However, it can be seen that the predictions of the TriboForm model are more accurate compared to the Coulomb friction model for the drawing depths of 20 [mm] and 40 [mm]. For the drawing depth of 60 [mm], the average error in the strains becomes larger for the predictions of the TriboForm model than for the Coulomb model.

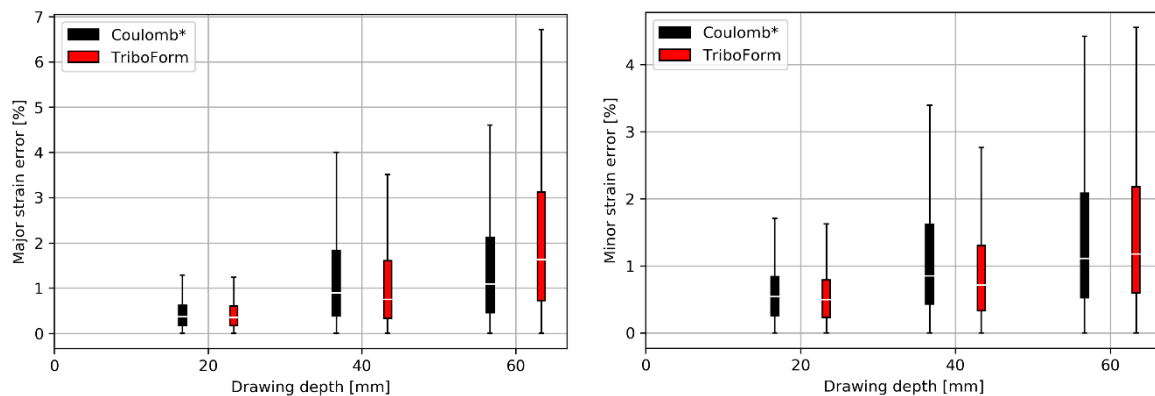


Figure 4. Mean absolute error in the (left) major and (right) minor strain between the experimental results and the strain predicted using the different tribological models; the classical Coulomb friction model, using an optimised coefficient of friction is indicated with Coulomb*.

The error in the strain is further investigated by isolating three areas that undergo different deformation modes, i.e. quasi-uniaxial tension, deep-drawing and biaxial stretching. The different areas show a large symmetry and are shown in Figure 5. The boxplots of the absolute error in these areas are shown in Figure 6 - Figure 8. For all deformation modes, the error in the predicted strains increases with an increase in the drawing depth. For the quasi-uniaxial tension mode, i.e. Figure 6, it can be seen that the error in the predicted strains for the TriboForm model are lower than for the Coulomb friction model for all drawing depths, thus indicating that the predictions for a uniaxial deformation are more accurate with the advanced model. For the deep-drawing mode, i.e. Figure 7, the predictions of the TriboForm model are less accurate than the Coulomb model for the predicted major strain. However, for the minor strains, the reverse holds. For the stretching mode, i.e. Figure 8, the predictions of the TriboForm model for the major strains are again less accurate than for the Coulomb friction model. However, in this case, for the minor strains, the accuracy of the two models is comparable. Clearly, the deformation mode influences the model accuracy.

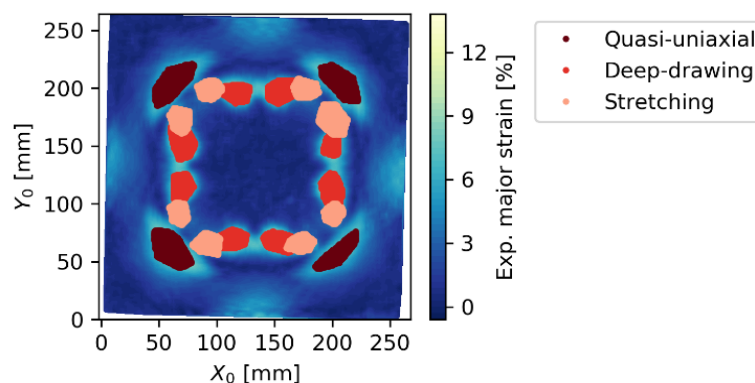


Figure 5. Areas used for the analysis of the different deformation modes seen in the cross-die experiment.

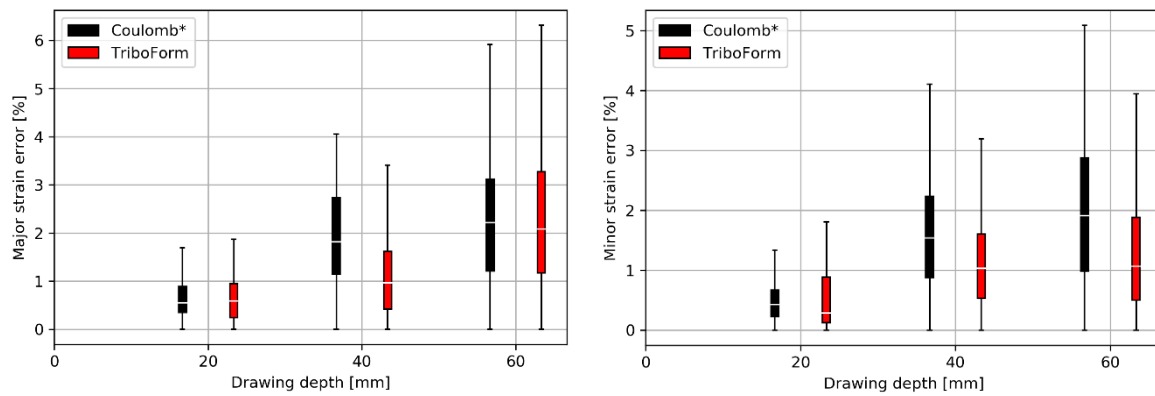


Figure 6. Mean absolute error in the (left) major and (right) minor strain in the area subjected to quasi-uniaxial tension between the experimental results and the strain predicted using the different tribological models.

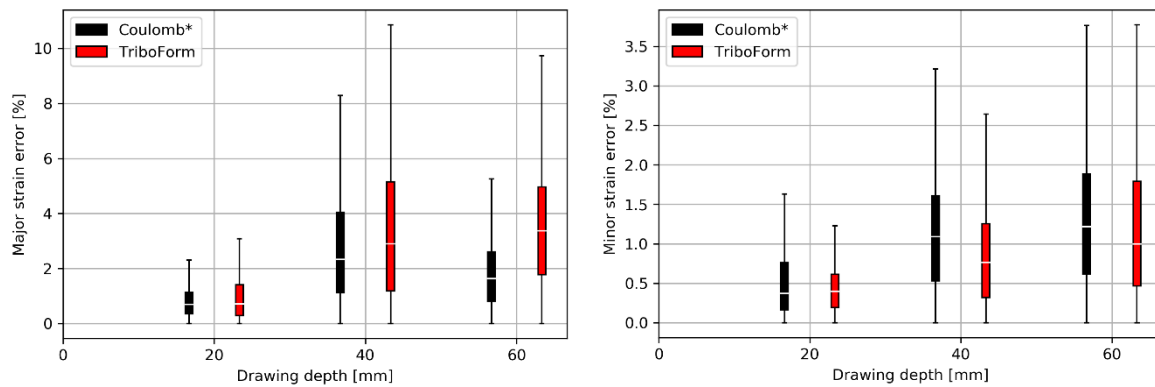


Figure 7. Mean absolute error in the (left) major and (right) minor strain in the area subjected to deep-drawing between the experimental results and the strain predicted using the different tribological models.

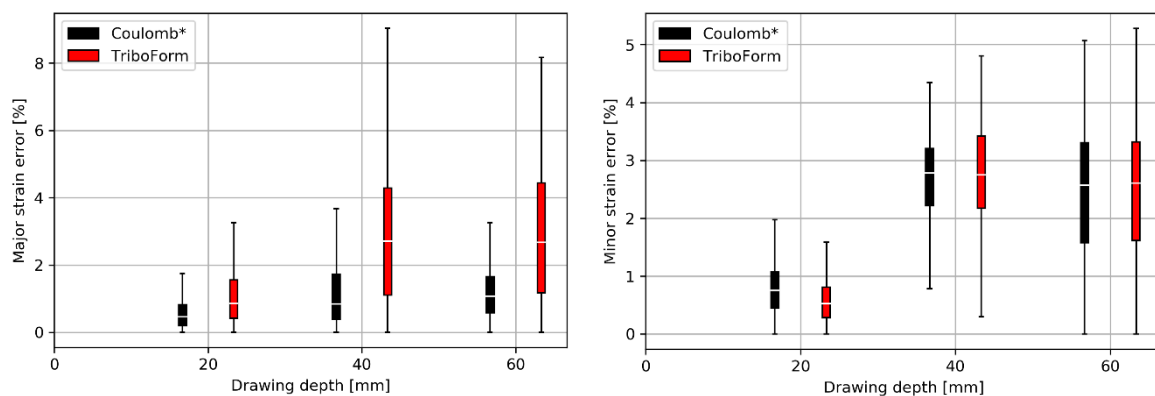


Figure 8. Mean absolute error in the (left) major and (right) minor strain in the area subjected to biaxial stretching between the experimental results and the strain predicted using the different tribological models.

4. Discussion

Two models were compared in this work, i.e. the commonly applied Coulomb friction model, using an optimised friction coefficient to accurately capture the experimentally observed material draw-in, and an advanced friction model, i.e. the TriboForm four-parameter model. The optimised friction coefficient used for the classical Coulomb model represents the highest global accuracy that can be obtained using a constant coefficient of friction [8]. The procedure used to obtain this coefficient of friction, i.e. fitting the numerically predicted draw-in to the experimentally measured draw-in at the set blank holder force, is in practice not feasible. Thus, the results presented in this work should be used as a guideline that illustrates the feasibility of the Coulomb friction model in complex forming simulations.

The results showed a clear difference between the predictions of the two different tribological models and the experimentally measured major and minor strains. The accuracy of the two predictions varied with the selected drawing depth and the area investigated. For the global average accuracy of the predicted strains, it was seen that the TriboForm model is, on average, more accurate than the Coulomb model for small drawing depths. However, the Coulomb model was more accurate for large drawing depths, indicating that the friction predicted by the advanced model for these large drawing depths was erroneous. A possible explanation for this is found in the areas where the error was largest for the TriboForm model, see the arrows in Figure 3(c, right). In these areas, the pressures are over-predicted by the Finite Element model. The classical Coulomb friction model does not incorporate a pressure dependency, while the TriboForm model does. The result is that for the TriboForm model, the friction coefficient in these areas is drastically increased, resulting in an increase in the predicted strains and thus a large difference between the experimental results and the predictions.

The comparison between the different deformation modes revealed that the accuracy of the TriboForm model compared to the Coulomb model depends on the deformation mode applied. In case of a quasi-uniaxial deformation mode, the TriboForm model shows a significant improvement over the accuracy of the Coulomb model. However, the predictions using the TriboForm model are less accurate in the other investigated loading conditions, i.e. deep-drawing and stretching. Here, the Coulomb model showed more accurate results for either the major or minor strains, depending on the deformation mode investigated. The explanation for these differences is found in the incorporation of the strain dependency in the TriboForm model, which does not include complex deformation modes, but rather assumes a uniaxial strain in the prediction of the strain influence on the coefficient of friction.

5. Conclusion

In this work, a quantitative analysis on the current state-of-the-art in tribomechanical modelling was performed to investigate the accuracy of these models in a well-defined, complex forming process. A cross-die deep-drawing experiment was performed and the strains were measured after the sheet metal was deformed to different drawing depths. The material used was a commercial uncoated deep-drawing sheet steel. Two tribological models were investigated, i.e. a classical Coulomb friction model, where the coefficient of friction was optimised to accurately capture the experimentally measured material draw-in, and an advanced friction model, which predicts the coefficient of friction based on the applied pressure, sliding velocity, temperature and strain.

The results showed that the accuracy of the two models varies depending on the accuracy of the Finite Element predictions and the deformation mode applied to the material. The advanced friction model shows an increased accuracy over the classical Coulomb friction model in the case of a uniaxial deformation mode and if the applied pressure is accurately predicted by the numerical model.

While the optimisation routine used to obtain the optimal coefficient of friction, as used in this work for the classical Coulomb friction model, is practically infeasible, the advanced friction model shows promise in prediction the evolution of the coefficient of friction in complex forming processes. However, a clear dependency of the accuracy on the applied deformation mode was found, indicating that the accuracy can be improved if complex deformation modes are incorporated into the friction model.

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