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Friction and lubrication modelling in sheet metal forming: Influence of local tool roughness on product quality

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Abstract. To improve the accuracy of forming simulations, advanced friction models are increasingly used in the industry. These models account for the physical properties of the sheet, tool and lubrication and describe the tribological conditions during the forming operation. One of the main influencing factors on the tribology system, and therefore the friction coefficient, is the surface roughness of the tools. Until now, it is often assumed all tools have the same uniform surface roughness. In reality however, the tool might have different surface conditions dependent on the type and location of the tool. That is, the blank holder might be differently polished than the punch, and sharp radii might have a different tool roughness compared to flat areas. This paper investigates a significant number of tool measurements from different tool sets from Volvo Cars, and quantifies the effect of local surface conditions on product quality.

1. Introduction

Sheet metal forming is a manufacturing technology widely used within the automotive industry. When in production, sheet metal formed parts are created at a high rate with consistent quality. To acquire a part of high quality, knowledge on the friction and lubrication conditions is essential. In fact, friction conditions can be more influential than the variation of sheet material properties or stamping process settings [1]. The friction conditions between the forming tools and the sheet material differs locally and over time. More specifically, these conditions depend on the local pressure, sliding velocity, interface temperature, plastic strain of the sheet material, the type and amount of lubrication and the surface topography of both the sheet and the stamping tools [2, 3]. For the latter parameter, it is often assumed that the surface roughness is the same for all tools and uniform across the tool geometry. Most of the times, the tools are polished manually and often performed by multiple polishers. Polishing is therefore not done equally for all tools and across their surfaces. Curved surfaces, for instance, are usually more thoroughly polished than flat surfaces. This paper therefore studies the influence of the tool type; die, blank holder and punch, as well as the influence of the location on the tool on the surface roughness. This is done through a statistical analysis of a significant amount of surface measurements from different tool sets from Volvo Cars. The influence of the tool surface roughness variations on part quality is subsequently shown on a door inner part from Volvo Cars by making use of AutoForm.

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To be able to study the influence of the tool roughness on the simulation results in AutoForm, the TriboForm friction model is used [4, 5]. The statistical analysis of the tool surface measurements is performed in Section 2. In Section 3, the statistical results are applied to a simulation of a rear door inner part from Volvo Cars. Finally, the conclusions and recommendations are given in Section 4.

2. Statistical analysis of surface measurements

This section contains information on the performed measurements and the surface characteristics considered.

2.1. Specifications

Over a period from 2015 to 2022, surface measurements have been performed on a significant number of production and try-out tools at Volvo Cars. In this study, a total of 100 surface measurements are analyzed corresponding to polished and uncoated cast iron tools used in cold sheet metal forming processes. These measurements are taken of each of the tool types shown in Figure 1. Of the total amount of surface measurements, 39 are from dies, 41 from blank holders and 20 from punches. The surface measurements are taken from different locations at both flat and radii areas. Figure 2 shows an example of a die of a rear door inner part and the locations at which surface measurements have been taken.

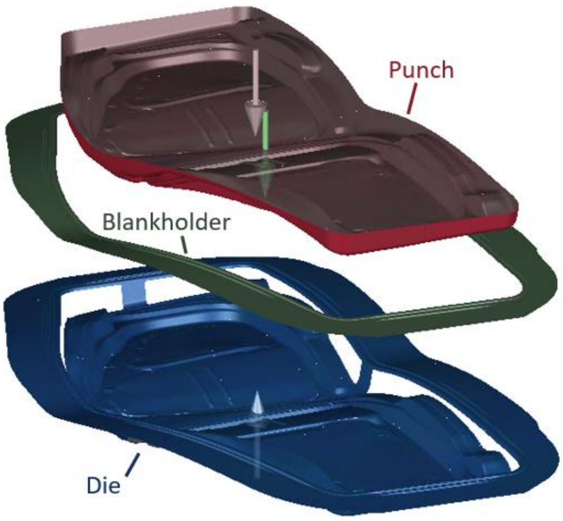


Figure 1. Tool set of a rear door inner part in AutoForm.

Figure 2. Example of surface measurement locations of a rear door inner part.

The surface characterization was performed using a surface replication technique in combination with the NanoFocus µsurf system to perform 3D surface measurements. Before the scanned 3D surface data is used, the data is processed (straightened and filtered) as described in [4].

From the surface measurements, the Sa-parameter is used as a measure for the surface roughness, which is the arithmetic mean height of the surface and is commonly used in the industry. Additionally, the radius of each surface is determined. This is done by fitting a second order polynomial through the rough surface data. Subsequently, the radius is computed in each direction of the surface, with the smallest found radius taken as the radius of the surface. Based on the computed radius, a distinction is made between flat and curved surface measurements.

2.2. Results

Figure 3 shows the Sa-roughness values of the total batch of measurements. On the left, the Sa-roughness value is plotted for each measurement. Within the box plot, both the median and the mean value are shown by respectively the green and the black line. The right side shows the probability density function of Sa-roughness values of all surface measurements, including the median and the mean value as thick horizontal lines.

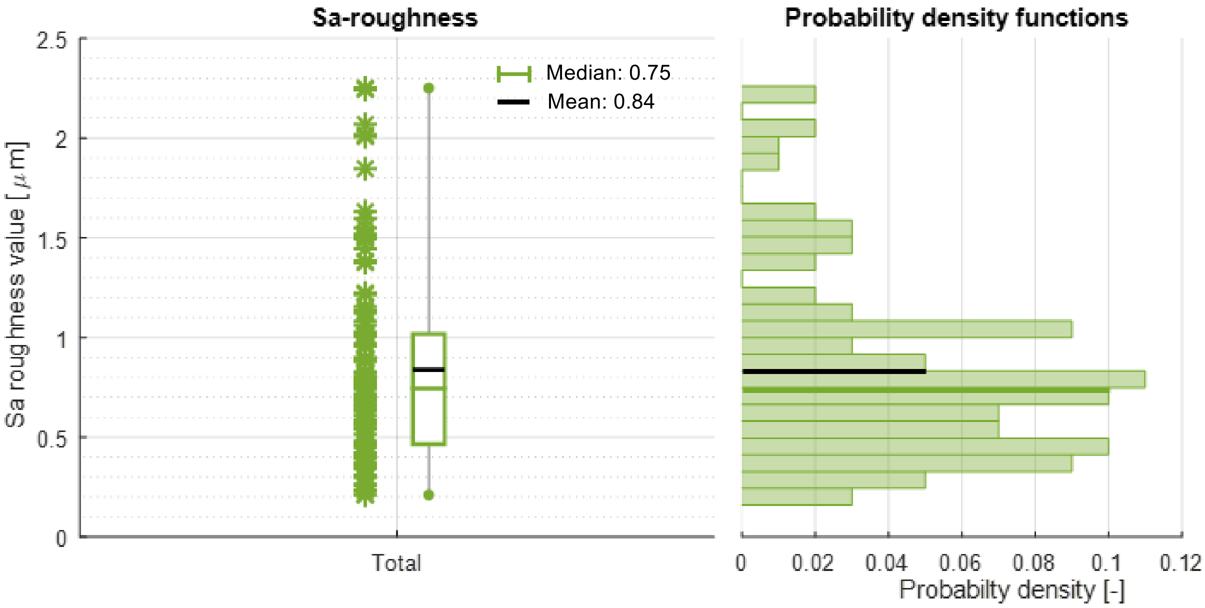


Figure 3. The Sa-roughness plotted for all 100 surface measurements.

From the probability density function it is shown that the Sa-roughness distribution is skewed and contains one-sided outliers with high roughness values. The median value is used within this study as the value shows a higher robustness against outliers. The median, with a value of 0.75 μm, is found in an area with a higher density of measurements compared to the mean, which has a value of 0.84 μm.

Splitting the total set of measurements into measurements belonging to the die, punch and blank holder, allows to see differences in surface roughness between the three tool types. The Sa-roughness values of each tool type are presented in Figure 4.

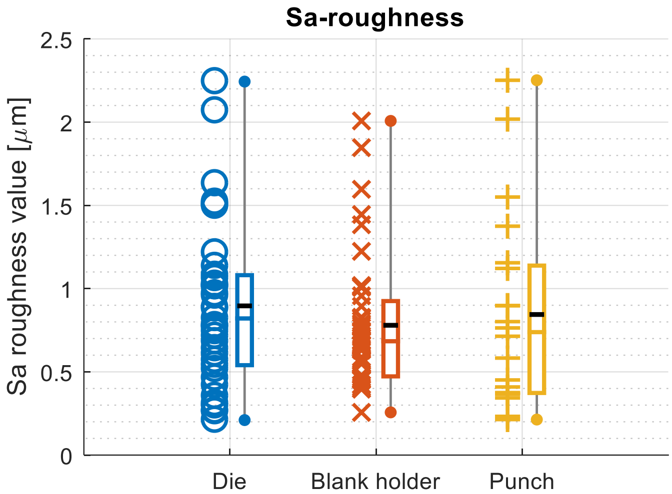


Figure 4. The Sa-roughness distributions of the die, blank holder and punch.

Table 1. The median and mean Sa-roughness value in μm corresponding to each tool type.

	Median	Mean
Die	0.82	0.90
Blank holder	0.68	0.78
Punch	0.74	0.84

The spread of Sa-roughness values is the largest for the punch, followed by the die and then the blank holder, as displayed by the height of the box plots. The median and mean values of the die are higher than those of the blank holder and the blank holder has higher values compared to the punch, as can also be seen in Table 1.

As seen in Figure 4, there exists a significant spread in surface roughness values for each of the tool types. This demonstrates that the tools have different surface conditions, which might depend on the location on the tool. That is, the blank holder might be differently polished than the punch, and sharp radii might have a finer tool roughness compared to flat areas. For this reason, a distinction is made between flat and curved areas as shown in Figure 5, where the radius of each measurement is plotted against the Sa-roughness. The surfaces are divided into two groups, one with measurements on curved surfaces and one with measurements from flat surfaces. Surfaces with a radius smaller than 20 mm are considered curved and measurements with a larger radius are considered flat. The dashed line in Figure 5 shows how the measurements are divided.

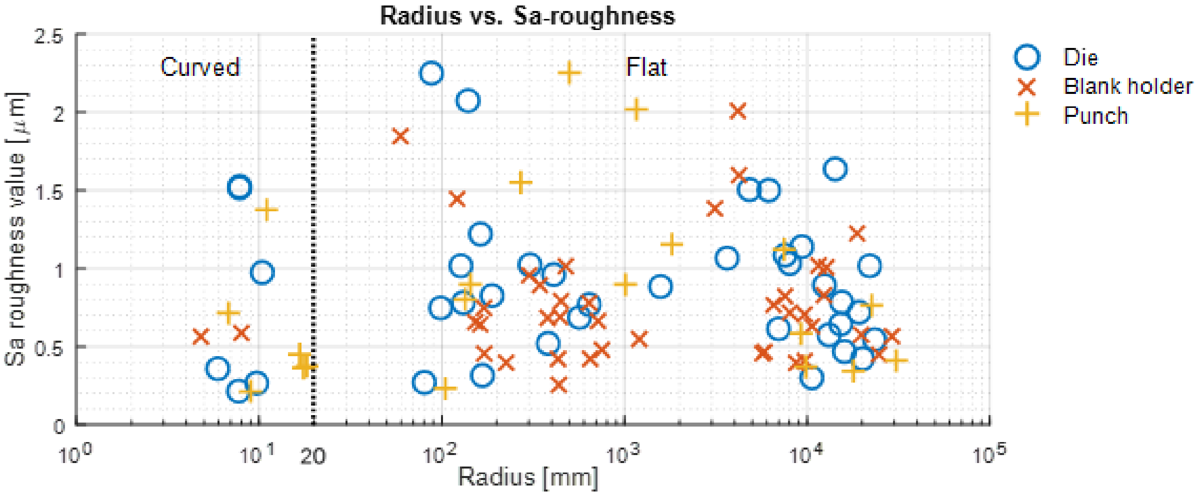
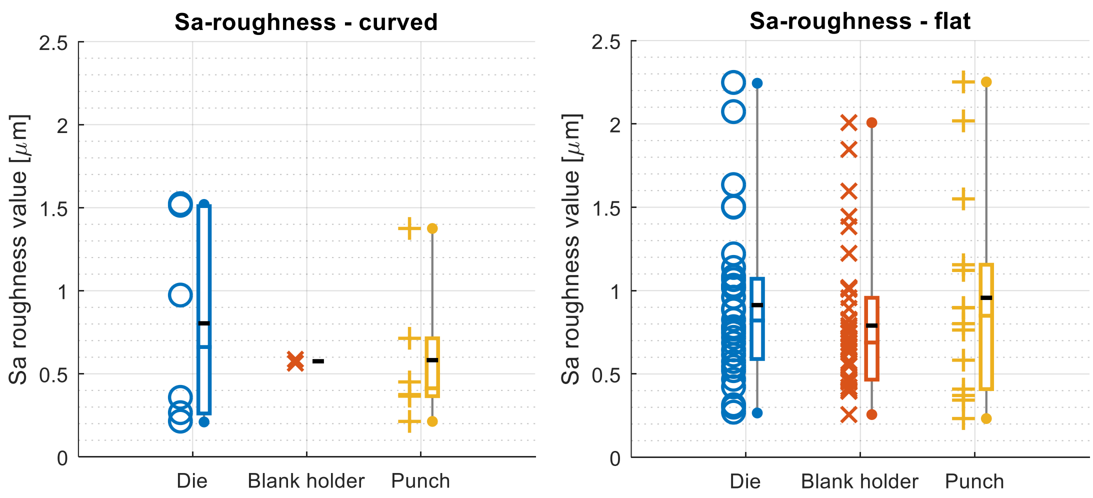


Figure 5. The Sa-roughness plotted against the radius for all surface measurements of each tool type.

In total, fourteen surface measurements have been performed on curved surfaces. Six measurements correspond with the die, two measurements belong to the blank holder and the remaining six belong to the punch.



(a) Curved surface measurements **(b)** Flat surface measurements

Figure 6. The Sa-roughness plotted against the radius for all surface measurements of each tool type in case of flat measurements (a) and curved measurements (b).

In Figure 6, the Sa-roughness of the curved and flat measurements are plotted separately for each tool type. From Figure 6a, it can be noticed that the measurements corresponding with the die show a large spread and that the mean and median values of the die are relatively high, as can also be seen in Table 2. This is caused by two outlying measurements with an Sa-roughness value close to 1.5 μm. The six curved punch measurements show less spread, with a relatively low median value of 0.41 μm. Of the set of blank holder measurements, only two are considered curved, resulting in equal mean and median values.

The Sa-roughness values corresponding with flat measurements are shown in Figure 6b. The mean and median values corresponding with the punch are higher than those of the die. Also, the spread of points is the highest for the punch. The measurements that belong to the blank holder on average have the lowest Sa-roughness values.

From Figure 6a and 6b, it is shown that the Sa roughness is lower for curved surfaces than for flat surfaces, which is also presented in Table 2. The largest difference is found for the punch measurements, with the median value being more than a factor two larger for flat surfaces.

Table 2. The median and mean Sa-roughness values in $\boldsymbol{\mu m}$ of each tool type, separating curved and flat surface measurements.

	Median		Mean	
	Curved	Flat	Curved	Flat
Die	0.66	0.82	0.80	0.91
Blank holder	0.58	0.69	0.58	0.79
Punch	0.41	0.85	0.58	0.96

3. Numerical analysis

To demonstrate the effect of different roughness regimes on product quality, numerical analyses are performed on a rear door inner part from Volvo Cars. The tribology system present, consists of a mild steel (CR3-ZM) with an average sheet roughness of 1.6 μm. The sheet is uniformly lubricated with Fuchs Anticorit PL3802 39S with an amount of 0.8 g/m^2. The tool material is a nodular cast iron (GGG70) with a surface roughness depending on the applied roughness regime.

Four different cases are evaluated, see Table 3. Case 1 uses Coulomb friction with a fixed value of the friction coefficient of 0.15. The other three cases use TriboForm friction, making use of the characteristics of the real tribological system. Case 2 utilizes a uniform surface roughness distribution for all tool types, using the median value of 0.75 μm. Case 3 uses tool type dependent roughness and uses the median values shown in Table 1, using all measurements independent of the surface radius. In the last case, Case 4, also radius-dependency is taken into account, using the summarized results shown in Table 2 corresponding to the median values. In this case, surfaces with a radius smaller than 20 mm are considered to be curved and use a different tool roughness value compared to flat areas.

Table 3. The four analyzed cases and their corresponding tool roughness values in μm.

Case	Description	Die		Blank holder		Punch	
1	**Coulomb friction 0.15**	-		-		-	
2	**TF, tool independent**	0.75		0.75		0.75	
3	**TF, tool dependent**	0.82		0.68		0.74	
		Curved	Flat	Curved	Flat	Curved	Flat
4	**TF, tool & radius dependent**	0.66	0.82	0.58	0.69	0.41	0.85

Figure 7 shows the difference in friction coefficients between Coulomb and TriboForm friction using three different values for the Sa-roughness of the tools. Here, the dependency of TriboForm friction on the pressure and the amount of strain in the sheet is shown, whereas Coulomb friction remains constant. Due to the relatively low lubrication amount, the velocity dependency of the current tribology system is minor. TriboForm friction shows that with an increase in pressure of the tool on the sheet, the friction coefficient decreases. Also, the friction coefficient decreases with increasing the strain in the sheet material. Furthermore, with an increasing tool-roughness, the friction coefficient increases as well, which is most significant for low pressure and strain values. The three friction models converge for higher values of pressure and strain.

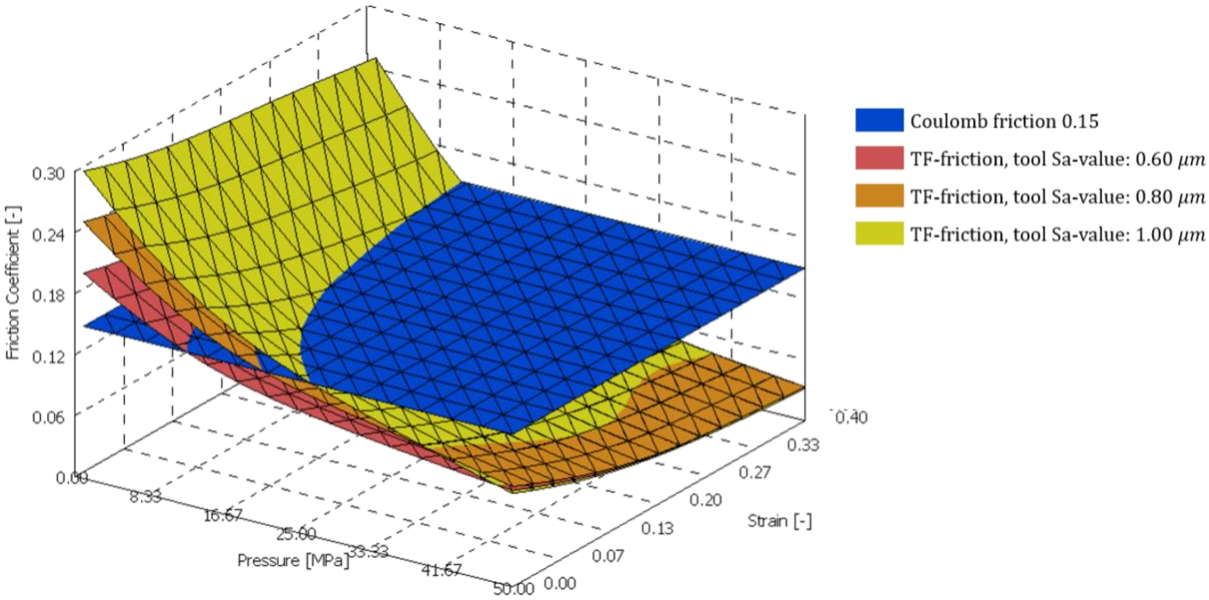


Figure 7. Comparison of Coulomb friction with TriboForm friction for different tool roughness values at a sliding velocity of 50 mm/s and a temperature of 20 $°c$.

The simulation results of the four cases are compared at the bottom end of the closing. Comparison is done using Advanced Formability (see Figure 8) in the AutoForm R10 software. Non-critical simulation results are expected from try-out and production of the rear door inner part, indicated by Volvo Cars.

The simulation results of Case 1 using Coulomb (Figure 8a), show that the part fails at multiple locations, which are encircled in red and are mostly found on the left hand side of Figure 8a. The fractures are clearly visible from the FLD, showing that Coulomb is too conservative in predicting the quality of the part.

The results of Case 2, using TriboForm friction with average tool roughness for all tools, are shown in Figure 8b. The FLC is not violated and hence no fractures are predicted. However, the part is still considered critical as excessive thinning and risk of splits occur at the encircled locations.

For Case 3, where each tool type has a different Sa-roughness value, the results are displayed in Figure 8c, which are similar to the results of Case 2. This is as expected, as the roughness values of each tool type are comparable and do not deviate much from the median value used in Case 2 (see Table 3).

The results of Case 4, which distinguishes between flat and radii areas on the tool surface, are shown in Figure 8d. The part becomes less critical with a reduction in excessive thinning areas and risk of splits. Overall, the parts become more safe with respect to Cases 2 and 3 and critical areas only occur at sharp radii locations.

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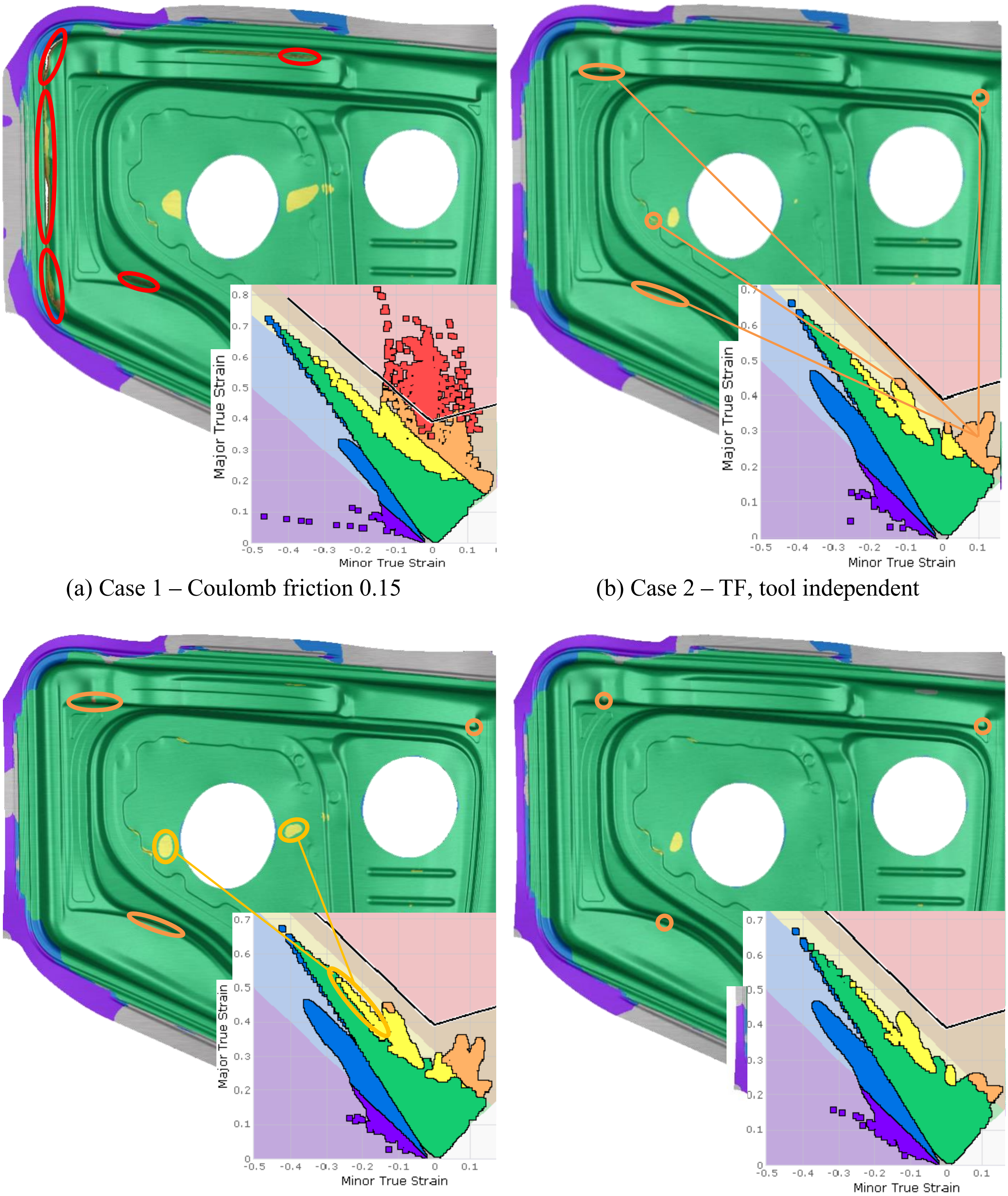


(a) Case 1 – Coulomb friction 0.15

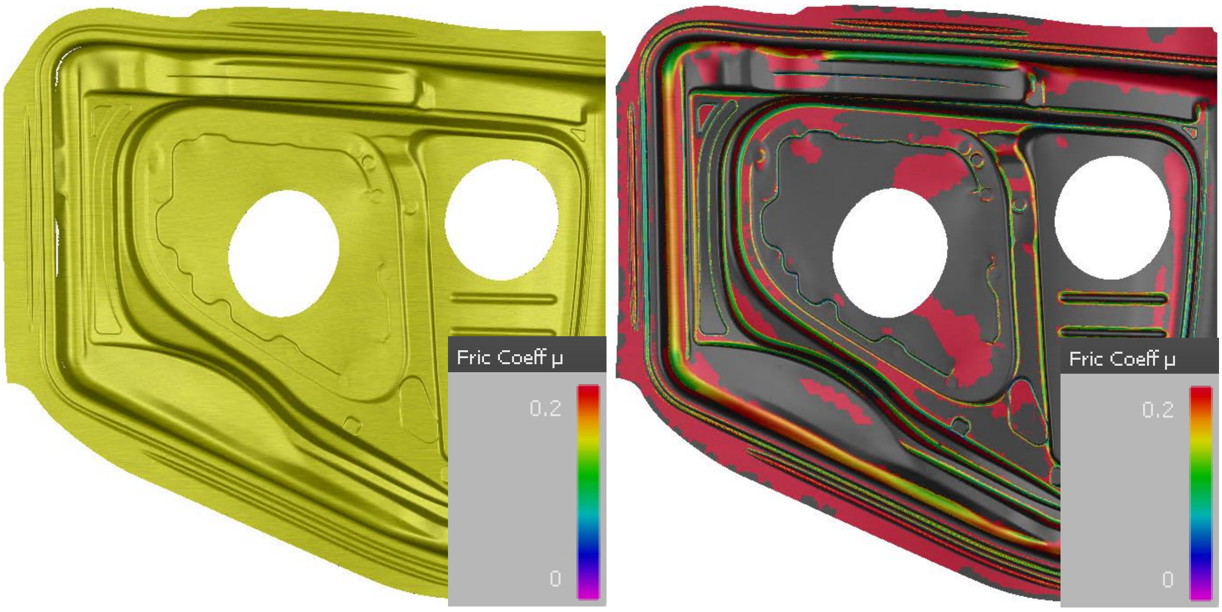
(b) Case 2 – TF, tool independent

(c) Case 3 – TF, tool dependent

(d) Case 4 – TF, tool & radius dependent

Figure 8. Advanced formability results of all four cases at the end of drawing, showing the formability across the part as well as the FLD.

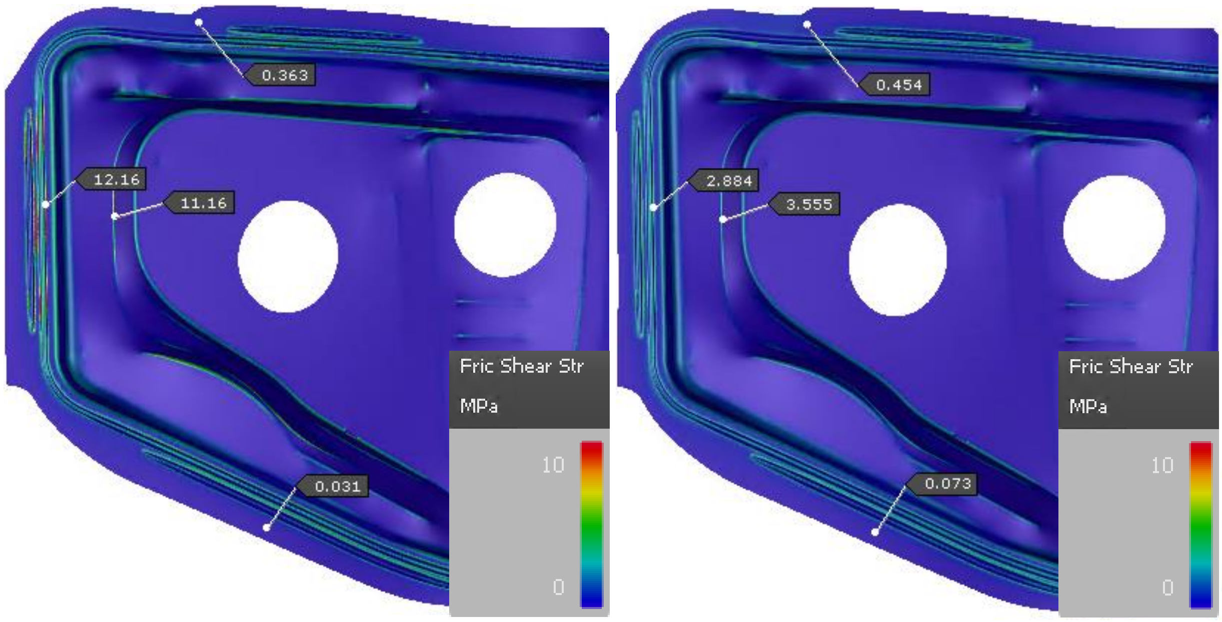
The significant difference between the results using Coulomb friction and TriboForm friction can be explained by Figures 9 and 10, which show the frictional behaviour of Cases 1 and 2 across the part geometry.



(a) Case 1 – Coulomb friction 0.15 (b) Case 2 – TF, tool independent

Figure 9. The friction coefficient across the part surface in contact with the punch for Cases 1 and 2.

On the left, Figure 9a, the uniform friction coefficient of Case 1 is shown (Coulomb friction 0.15). On the right, Figure 9b, the friction coefficient is shown for Case 2, which varies in accordance with the friction model shown in Figure 7. That is, regions with high values of pressure and/or strain show a lower friction coefficient. As can be seen, these regions are mainly found on curved regions such as the drawbeads. Furthermore, it can be observed that flat areas have a relatively high friction coefficient, which is displayed in red. The friction coefficient is not computed for areas which have not been in contact with the tool and are displayed in grey.



(a) Case 1 – Coulomb friction 0.15 (b) Case 2 – TF, tool independent

Figure 10. The friction shear stress in MPa across the part surface for Cases 1 and 2 at 20 mm prior to closing, when the first splits appear for Case 1.

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Figure 10 shows the friction shear stress for Cases 1 and 2 across the part geometry 20 mm prior to closing, when the first splits appear for Case 1. The friction shear stress is computed as the friction coefficient multiplied with the normal pressure. As can be seen, curved regions of the part correspond to high friction shear stress values. These regions therefore have a relatively large impact on the forming process, despite having relatively low friction coefficient values.

Using Coulomb friction, the friction coefficient (fixed value of 0.15), and therefore also the friction shear stress, is larger in curved regions compared to TriboForm Friction, see Figure 9. On the other hand, the friction coefficient in flat sheet areas is lower compared to TriboForm friction, but because of relatively low contact pressures at these areas, the effect on shear stress is relatively low, see Figure 10. Overall, this leads to a more critical simulation, resulting in splits, as seen in Figure 8a.

Comparing the results from the three cases using TriboForm, it is shown that Case 4, with radius dependency, shows the least critical results. By lowering the tool-roughness in curved regions, the friction coefficient decreases, resulting in a reduction of the friction shear stress at these areas. As radii area have the highest contribution to the friction shear stress, these also have the highest impact on the part quality. The results of Case 4 are expected to give the most accurate simulation results and are in line with the expectations from try-out trials at Volvo Cars.

4. Conclusions

From the statistical analysis it was shown that the tools have a Sa-roughness value of 0.75 and 0.84 μm (median and mean, respectively). Furthermore, a slight difference in surface roughness values between tool types was found. A larger difference was found between curved and flat areas. However, the data set of curved measurements was relatively small and more measurements are required to perform a proper statistical analysis. To extend the study, additional surface measurements should be evaluated and care should be taken regarding the location on the tool the measurement is performed. That is, the measurements should be taken in areas in contact with the sheet and not from e.g. offsetted tool areas or non-bearing areas.

From the numerical results it was concluded that Coulomb overpredicts frictional shear stresses leading to a too conservative simulation. Using TriboForm and differentiating in Sa-roughness values between curved and flat areas, results becomes less critical and in line with expectations from try-out results at Volvo Cars. The difference in simulation results of tool type independent and dependent TriboForm friction is small, which is due to the slight difference in surface roughness values of the different tool types.

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