An industrial application case to predict galling in hot stamping processes

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Abstract. Severe tool wear is an unwanted phenomenon which occurs widely during hot stamping processes due to extreme process conditions like high temperatures and the absence of lubricant. Galling is a wear mechanism in the form of adhesive wear in which some material from the sheet transfers to the tooling. In a longer term, the build-up of material on the tool can damage the sheet in the form of scratches and can negatively affect the heat transfer between sheet and tool. Therefore, it is important to develop advanced models to predict and control tool wear and galling during hot stamping processes. More recently an advanced friction model for hot stamping processes has been introduced to accurately describe frictional behavior of 22MnB5-AlSi. This study aims to further extend the advanced friction model of 22MnB5-AlSi into a galling prediction tool by first evaluating possible galling initiation models and next assessing growth models. These models are calibrated using experimental data from hot strip draw tests performed at Tata Steel. This results in a multi-dimensional galling model as a function of temperature, pressure, strain and also on the relative sliding distance in contact between the tool and the sheet. Finally, the predicted galling distribution on the tooling surfaces for two industrial parts from Volvo Cars are verified. The galling locations are accurately found on the parts by the applied galling model.

1. Introduction
Hot stamped parts in body-in-white applications are of a great interest due to their superior mechanical properties [1]. A commonly used material in direct hot stamping process is the ultra-high boron strength steel 22MnB5 with an aluminum silicon (+AlSi) coating to improve its corrosion resistance. For the tooling, the tool steel material with a coating layer to improve wear and frictional behavior is often utilized, which together with the 22MnB5 (+AlSi) form the most commonly used tribology system for hot stamping processes in the automotive industry. However, still one of the known issues during hot stamping processes is galling, which is a type of adhesive wear [2,3].

Galling occurs mainly due to the extreme process conditions during hot stamping with very high temperatures and the absence of lubricant, which causes particles from the softer sheet surface to transfers to the relatively hard tool surface which can affect the tribological behavior [2,3]. In a longer term, over multiple production cycles, the particles accumulated at the tool surface can eventually
damage the sheet surface, observed in the form of scratches, and can negatively influence the heat transfer between sheet and tool during e.g. the quenching process. These unwanted phenomena cause a disturbance in the production batch, because the tooling needs to be cleaned or replaced [4]. Hence, developing advanced models to predict galling in forming simulations can significantly benefit achieving a better understanding of the process and tribological conditions which result in initiating galling in the forming process.

More recently, to describe the frictional behavior in forming simulations of hot stamping processes, an advanced friction model has been introduced by TriboForm® [4]. This friction model can predict friction under different process conditions such as a range of pressure and temperature and basically can substitute the conventional constant Coulomb friction modelling in hot stamping simulations [4,5]. For this study, the contact model implemented in the TriboForm advanced friction model is further adopted to predict galling. Also, a galling initiation model and a lump growth model are implemented, which are collectively calibrated based on the results from a series of hot strip-draw experimental testing by Tata Steel. Finally, the galling model is validated by comparing the severity of galling behavior observed for two industrial hot stamping parts, an A-pillar reinforcement and a side member from Volvo Cars, with the predicted galling distribution on the tooling surfaces.

2. Modelling approach

The 3D surfaces topographies from 22MnB5 (+AlSi) blank and tooling surfaces are the basis for both friction and galling models. The 3D surface of the sheet is captured after initial heating of the blank to a temperature of 930°C and then cooling it down, which resulted in a surface roughness of around 2 µm (Figure 1). The tooling surface belongs to a standard tool steel tooling from production with a typical roughness value in the range of 0.6 µm [6]. Furthermore, the material model according to hardening law proposed by Abspoel and van Liempt for hot forming is considered [7].

![Figure 1. Surface topographies of 22MnB5 (+AlSi) after heat treatment and tooling surface.](image)

2.1. Galling models

The contact area, coefficient of friction and asperity shape from the contact model of TriboForm Solver® [5] are used as inputs to the implemented galling models, namely the galling initiation model and a lump growth model. The galling initiation model shows the criteria for which an asperity will be a contributing factor to galling. This is followed by the lump growth model, which shows how adhered material will be deposited on the galling initiated asperities.

Before an asperity grows in size according to the lump growth model, it needs to be determined if the asperity is initiated for galling. A criterion needs to be set to check whether the composition of the asperity in combination with the input parameters of the process is suited to be initiated. In this study, the coating fracture initiation (CFI) criteria is used which is based on the plane strain fracture toughness of the coating as a threshold for galling initiation of an asperity.
In the next step, the lump growth model is implemented by following a couple of steps, first the separation height is determined to know which tool asperities are in contact and what their penetration is into the softer counter surface. Then, the material transfer from the sheet to the tool is determined in two steps: 1) determine transferred volume and 2) determine deposit layer. Then the stability is evaluated, because the material that is able to transfer only adheres when the asperity can hold the forces during sliding: 1) determine stresses within the asperity and 2) evaluate stability cases.

Finally, the adhered layer, according to one of the stability cases in the step before, is included in the new dimensions of the asperity. This cycle is repeated, which leads to multiple extra layers on the initial asperity, called growth of the asperity. Full details of the lump growth models and procedure can be found in the previous studies by van der Linde et al. [8].

2.2. Calibration
To simulate the conditions of a hot stamping process a series of hot strip draw tests are performed by Tata Steel. Using a roller heat furnace the blank is heated to a temperature of 930°C for 6 minutes to ensure full austenitization of the material [8]. The specification of strip and tool are given in the Table 1. The strips are then transferred to the stripdraw setup and tested with an interface temperature range from 450-750 °C under the nominal pressure of 2.5 and 5 MPa and a velocity of 100 mm/sec. Furthermore, a series of line measurements and 3D optical confocal measurements are performed using a Mahr PKG120 (cut-off 0.8mm) to determine the amount of area and volume of adhered wear at the locations with the greatest amount of wear (Figure 2).

The line measurements contains worn and unworn sections of the tooling surface and the confocal images provide a 3D height distribution of the tooling surface with the highest amount of observed wear. The line and 3D measurement are used in combination to determine the adhered volume, by first defining the reference height from the line measurement and then overlapping the 3D surface data on the reference line to quantify the adhered volume. Finally, the experimentally measured data is used for calibrating the lump growth model by using the correlation between worn volume and transferred volume.

| Table 1: Specification of tested strip and tooling. |
|-----------------|-----------------|-----------------|
| **Strip**       | **Tool**        |                  |
| Substrate       | 22MnB5          | Material        |
| Coating         | Al-Si (7-11% Si)| Finish          |
| Ra (Rolling Direction) | 0.15 µm   | Hardness        |
| Ra (Transverse Direction) | 0.04 µm   | 48±2 HRC        |
| Dimensions      | 800 x 50 x 1.5 mm | Sₐ of testing tool |
| Sa (after heat treatment) | 1.9 µm | 0.20± 0.05 µm |

Figure 2. Schematic overview of both measurement techniques and its intersection.
3. Stamping simulations

Two industrial parts from Volvo cars, an A-pillar lower reinforcement and a side member, were studied (Figure 3 and 4). The simulation settings were following the standard settings at Volvo Cars to model hot stamping process using AutoForm® R8.0, including cyclic simulations considering the cooling channels to calculate the 3D heat conduction in the tool volumes. This leads to a more accurate surface temperature calculation.

The multi-dimensional friction model for the studied tribology system of 22MnB5 (+AlSi) and tool steel, is incorporated into the AutoForm simulation by using the TriboForm Plug-In®. The friction model also includes the galling model as a function of pressure, temperature, and strain over the sliding length. After running the simulations, the galling amount is projected back on the tooling surfaces using an in-house software.

The simulation results concerning the A-pillar reinforcement has been validated in the previous study by comparing the experimental and predicted thickness results [4]. For the current study, mainly the observed locations on the tooling surfaces with severe galling are compared with the predicted galling on the tooling surfaces.

Figure 3. (Left) The tooling surfaces for the A-pillar lower reinforcement and (right) the final product.

Figure 4. (Left) The tooling surfaces for the side member and (right) the final product.
4. Results and discussion

4.1. Calibration the galling models and calculating galling

The measured transferred volume from hot strip draw tests for a range of temperatures versus predicted worn volume by the galling model are shown in the Figure 5. Only experimental data points at the pressure of 5 MPa and the temperature from 500 °C to 700 °C are included as at 450 °C no clear correlation between line and 3D measurements can be found. Also, it was observed that at the highest temperature of 750 °C probably large lumps were removed that are also excluded from further analysis. The contact fracture galling initiation model (red line in Figure 5) shows an increase of adhered volume till a temperature of 625 °C and then a decrease is predicted, which corresponds to the experimental findings.

The obtained calibration parameters were then used to extend the galling model for a wider range of pressure, temperature and strains as shown in the Figure 5 (Right). To predict the galling amount for these ranges, the galling initiation model was applied within the TriboForm Solver®. To check whether a single asperity is able to initiate lump growth for galling the equation below is used. The initiation according to the CFI model uses the nominal pressure to calculate the stress intensity factor for its fracture criterion. The equation states that if the stress intensity factor (K₁) of the single asperity in question exceeds the plane strain fracture toughness of the coating layer that the asperity will initiate fracture. Subsequently, the adhered volume is calculated over sliding length for the range of pressure, temperature and strain, which results in the galling model as a function of these parameters.

\[
K_1 \geq K_{IC} \\
K_1 = \frac{Y}{\pi a}
\]

One important limitation is that during sliding contact both adhesive and abrasive wear are present, which are temperature dependent [9,10]. Therefore, the experimental data for the transfer volume shows adhered volume affected by abraded volume to an unknown extend. Also, the growth model is based on the adhesive galling, while compaction galling might also have a significant influence. However, the experimental adhered volume cannot distinguish between these two. Also, the procedure (position, measurement size) to determine the wear volume and/or wear height has a large effect on the results due to the inhomogeneity of the wear over the tool surface. Fracture of particles plays an important effect in compaction galling, another tests set up including deformation (for example strip drawing over a radius) could be interesting for calibration of the models.

![Figure 5](image-url)

**Figure 5.** (Left) The transferred volume measured from strip draw tests versus predicted worn volume by the galling models. (Right) The predicted galling height as a function of pressure and temperature.
4.2. Galling prediction for the industrial parts

As the galling amount or galling height is not exactly known, it is mainly possible to compare the location with severe galling on the real tooling with the predicted locations on the tooling surfaces. The A-pillar part has shown a high amount of galling at the outer radii of punch which is also predicted correctly using the galling model (Figure 6). Less amount of galling was predicted for the punch pad and die which corresponds with the observation on the real tooling by Volvo cars.

However, there were two over-predicted points at the inner radii which was not observed in practice. A further analysis showed no significant difference in sliding length compared to the neighbouring edges, hence, these locations are attributed to a numerical error during the projection of galling on the tooling and not to real galling predictions.

It is important to be noted that the prediction of galling amount projected on the tool depends on the temperature, pressure and strain of the sheet during forming and on the relative sliding distance in contact between the tool and the sheet. This explains then the difference between different tool parts due to the difference in cumulative sliding distance, as the sliding length for the die and punch pad is significantly less than the sliding length on the punch.

Regarding the side member, the punch has shown a severe galling in reality (Figure 7). The simulation results show that the galling model can predict the location of galling for the side member to a very good extent (Figure 7). The severe galling location occurs when the tooling is heated up to 525°C, though, this high tool temperature is not directly applied within the galling model, still the tooling temperature does influence the sheet temperature, which is used to predict the galling amount per time increment.

Further evaluation demonstrates that the combination of pressure, temperature and strain does not indicate severe galling, hence the long sliding distance on these spots causes the severe galling. The punch pad and the die do not suffer from galling, which is in line with the experience at Volvo Cars. More interestingly, the simulation results of the side member show a higher prediction of galling amount compared to the A-pillar, which is also in accordance with the experience from Volvo Cars.

Figure 6. The distribution of galling (g/mm²) on the outer radii of punch (right) and (left) inner radii views.
Figure 7. (Left) The observed galling at the tooling surface of side member which corresponds to (right) the distribution of predicted galling (g/mm$^2$) in the white boxes. Red boxes show the second location with high galling.

5. Conclusion and future work

In this study, the prediction capability of a galling model during hot stamping process has been studied for two industrial parts. To achieve this goal, first the original contact model of the TriboForm friction model is further developed and expanded with a galling initiation model and a lump growth model. The galling model is then calibrated by using the experimental data from hot strip draw tests and finally validated by comparing predicted galling locations with real parts. The calibration process was performed under a series of limitations as the exact amount of adhesive wear cannot be isolated from other forms of wear, namely compaction wear and abrasive wear.

Despite these limitations, a good match was found in terms of predicting the galling locations in both industrial parts which shows the high potential of the current model for predicting galling. However, as the severity of galling has not been measured in practice, it was not possible to compare the predicted galling amount with reality. The next step should focus on determining a quantitative approach to give an indication of galling risk based on the predicted galling amount.
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