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

J. Hol¹, J.H. Wiebenga¹ and B. Carleer²

¹ TriboForm Engineering B.V.
Hengelosestraat 500, 7521 AN, Enschede, The Netherlands
Web page: www.triboform.com

² AutoForm Engineering
Joseph-von-Fraunhofer-Str. 13A, D-44227 Dortmund, Germany
Web page: www.autoform.com

e-mail: j.hol@triboform.com

Abstract. In the stamping of automotive parts, friction and lubrication play a key role in achieving high quality products. In the development process of new automotive parts, it is therefore crucial to accurately account for these effects in sheet metal forming simulations. This paper presents a selection of results considering friction and lubrication modelling in sheet metal forming simulations of a front fender product. For varying lubrication conditions, the front fender can either show wrinkling or fractures. The front fender is modelled using different lubrication amounts, tool roughness’s and sheet coatings to show the strong influence of friction on both part quality and the overall production stability. For this purpose, the TriboForm software is used in combination with the AutoForm software. The results demonstrate that the TriboForm software enables the simulation of friction behaviour for varying lubrication conditions, i.e. resulting in a generally applicable approach for friction characterization under industrial sheet metal forming process conditions.

1. Introduction
The quality of sheet metal formed parts is strongly dependent on the tribology and friction conditions that are acting in the production process. These friction conditions are dependent on the utilized sheet material, tooling material and lubricant. This combination of factors is known as the tribological system [1] or tribology system. Choosing the optimal tribology system in an early stage of the design process enables to design products with optimal quality at minimal time and cost investment.

The quality of front fender products is in general strongly dependent on the friction and lubrication conditions (i.e. tribological conditions) that are acting in the actual production process. Tribological conditions change when the sheet material, coating and tooling material, lubrication type, lubrication amount or process conditions change. This can have a significant influence on both the part quality and the overall production stability as demonstrated in [2].
In this paper, the influence of lubrication amount, tool roughness and sheet coating type on the occurrence of fractures and winkle is demonstrated for a front fender product. For this purpose, the TriboForm software is used in combination with the AutoForm software. First the overall project approach will be outlined. Next, the stamping process of the front fender product will be introduced. A description of the project results including a variation study on lubrication conditions is provided. In the final section the conclusions are described.

2. Approach
Tribological conditions in metal forming processes are dependent on local process and lubrication conditions as demonstrated in [3, 4]. The TriboForm software allows for multi-scale modeling of a time and locally varying friction coefficient under a wide range of process conditions. The generated friction models can be easily imported in FEM simulations of forming processes such as the AutoForm software. The approach followed in this paper is visualized in Figure 1.

![Figure 1. Approach for friction and lubrication modeling in sheet metal forming simulations](image)

The modelling approach comprises three steps. In step 1, a TriboForm friction analysis is performed on a user-defined tribology system (see Section 2.1). A tribology data set is generated for the selected tribology system, which is exported to a friction file (see Section 2.2). Finally in step 3, the generated friction file is used in forming simulations using the AutoForm software.

2.1. Simulation of friction and lubrication conditions
The TriboForm software accounts for the actual tribology system used in production. For this purpose, information of the tribology system is required as a user input, i.e. the applied sheet material, coating and tooling material, lubrication type, lubrication amount and process conditions. This information can be extracted from a database, i.e. the TriboForm Library. The TriboForm Library includes multiple friction models for different tribology systems. These friction models are constructed using physically-based models, enabling friction modeling in the mixed lubrication regime. This is achieved by coupling a boundary lubrication friction model [5] and a hydrodynamic friction model [6].

2.2. Friction file
The TriboForm software calculates friction coefficients for a predefined range of process settings, i.e. local contact pressures, relative sliding velocities, plastic strains in the sheet material and interface temperatures. A four dimensional matrix is constructed containing friction coefficients for all possible combinations of process settings. To use this data-set within large scale forming simulations, and to guarantee computational efficiency, a four dimensional model is adopted to describe the calculated data points which is stored in a friction file (see Figure 1). Using the TriboForm software, a friction file can be created per tribology system, i.e. the sheet and tooling materials, coatings and lubricants used in actual metal forming production. A friction file has to be constructed only once for a specific tribology system, after which it can be used in different forming simulations where the same combination is used.
2.3. Stamping simulations

Next, the friction file can be easily used within an AutoForm simulation using the TriboForm FEM Plug-In integrated in AutoForm R7. That is, if an AutoForm simulation is started, the FEM Plug-In reads the friction file exported from TriboForm and enables the usage of the friction model within the AutoForm simulation. As a result, the constant coefficient of friction in AutoForm is replaced by the friction model. Now, a local- and time-dependent (nodal) friction coefficient is computed each increment and used in the computation of the equilibrium of the finite element model for the materials, coatings and lubricants used in actual metal forming production.

3. Front Fender application case

To show the influence of tribological conditions on an industrial application case, the front fender part of the Numisheet 2002 benchmark is studied in this paper. An impression of the front fender part is shown in Figure 2. The front fender part is produced using a coated mild steel sheet material with a thickness of 0.7 mm. Commonly used sheet coatings are Electrogalvanized (EG) and Hot Dip galvanized (GI), which will both be analysed in this paper. The sheet material is lubricated with a standard drawing oil. From measurements in production it is shown in [2] that the lubrication amount can range between 0.6 g/m² and 2.0 g/m² on both sides of the sheet. A lubrication amount of 0.6 g/m² and 2.0 g/m² will therefore be analysed to show the influence of lubrication amount on final part quality. The tooling material type is nodular cast iron, for which 2 different surface finishes are assumed: fine polished ($S_a = 0.2 \, \mu m$) and normal polished ($S_a = 0.4 \, \mu m$).

![Figure 2. Simulation set-up front fender in AutoForm (left) and final formed product (right)](image)

The TriboForm software is used to simulate the friction conditions for different tribology systems. The used tribology systems are selected from the default TriboForm Library, see table 1. In Section 3.1 the corresponding friction models will be discussed, in Section 3.2 the AutoForm simulation results including the TriboForm friction models will be evaluated.

| ID | Sheet material | Sheet coating      | Lubrication type | Lubrication amount | Tool material | Tool roughness               |
|----|----------------|--------------------|------------------|--------------------|---------------|------------------------------|
| 1  | Coated mild steel | Electrogalvanized | Drawing oil       | 0.6 g/m²           | Tool Steel    | $S_a = 0.4 \, \mu m$ (normal polish) |
| 2  | Coated mild steel | Electrogalvanized | Drawing oil       | 2.0 g/m²           | Tool Steel    | $S_a = 0.4 \, \mu m$ (normal polish) |
| 3  | Coated mild steel | Electrogalvanized | Drawing oil       | 0.6 g/m²           | Tool Steel    | $S_a = 0.2 \, \mu m$ (fine polish) |
| 4  | Coated mild steel | Hot dip galvanized | Drawing oil       | 0.6 g/m²           | Tool Steel    | $S_a = 0.4 \, \mu m$ (normal polish) |

Table 1. Evaluated tribology systems
3.1. Friction simulations

The friction and lubrication conditions corresponding to the tribology systems indicated in Table 1 are simulated using the TriboForm R2.0 software. The data required to simulate friction conditions, such as e.g. the 3D surface topographies, are extracted from the default TriboForm Library. Impressions of the 3D surface topographies for the different tribology systems are shown in Figure 3 to 5.

**Figure 3.** Impression sheet surface topography. Left: EG coated material. Right: GI coated material.

**Figure 4.** Impression lubrication amount on the sheet surface. Left: 0.6 g/m\(^2\). Right: 2.0 g/m\(^2\), whereby the blue transparent plane indicates the lubrication level.

**Figure 5.** Impression tool surface topography. Left: fine polished. Right: normal polished.

The TriboForm software simulates friction conditions by loading and sliding the tool surface onto the sheet surface, see Figure 6 (left). Predefined ranges of contact pressures, strains in the bulk material, relative sliding velocities and interface temperatures are used to construct the 4 dimensional friction model. The friction model corresponding to the first tribology system in Table 1 (ID = 1) is shown in Figure 6 (right).
Figure 6. Projection tool surface onto sheet surface (left) and friction model for tribology system ID = 1 for different strain levels in the sheet material (right).

Figure 6 (right) shows the frictional behaviour as function of pressure and sliding velocity for a fixed temperature of 21°C. The different planes indicate friction values for different strain levels in the sheet material, ranging from 0.0 to 0.4 in 5 steps. From the graph, a significant dependency on contact pressure and plastic strain in the sheet material is observed. That is, higher contact pressures and higher plastic strains in the sheet material result in lower friction values. The velocity dependency increases for an increasing strain in the sheet material, i.e. the higher the plastic strain, the more pronounced the velocity effect is, resulting in lower friction coefficients for increasing velocity.

Figure 7 demonstrates the frictional behaviour for the other 3 tribology systems listed in Table 1. Increasing the lubrication amount from 0.6 g/m² (tribology system 1) to 2.0 g/m² (tribology system 2) increases the velocity dependency, see Figure 6 (left). For strain levels larger than 0.2, a drop in friction values from 0.08 to 0.02 is observed for increasing velocity, indicating that friction occurs in the transition regime from mixed lubrication to full film lubrication. Reducing the roughness of the tooling from 0.4 µm (tribology system 1) to 0.2 µm (tribology system 3), result in a general decrease in friction coefficients, see Figure 6 (middle). The same trend in pressure / strain and velocity dependency is observed compared to the 0.4 µm roughness case. Changing the sheet coating from electrogalvanized (tribology system 1) to hot dip galvanized (tribology system 4) also results in a general decrease in friction values, see Figure 6 (right). However, in contrast to electrogalvanized material, no velocity effect is observed for the hot dip galvanized material when applying a lubrication amount of 0.6 g/m².

Figure 7. Frictional behaviour for a lubrication amount of 2.0 g/m² (left), Fine polished tool surface (middle) and Hot dip galvanized coating (right)
3.2. Front Fender simulation results

The generated friction models are exported to a friction file and used within AutoForm R7.0.2 to simulate the front fender part. The friction files are coupled to the material file by making use of the Lubrication File Generator in AutoForm. For the simulation a mild steel (DX54D) was used, with the process conditions and tool / blank geometry according to the Numisheet 2002 benchmark [7].

Figure 8 shows the distribution in friction values (left), Max Failure (middle) and the Forming Limit Diagram (right) corresponding to tribology system 1 (electrogalvanized mild steel). Results are shown for the side of the blank in contact with the punch. An isothermal temperature of 21°C was assumed for all simulations. Friction conditions are influenced by the nominal contact pressure, equivalent plastic strain and sliding velocity, resulting in a local- and time-dependent (nodal) distribution of friction coefficients, see Figure 8 (left). Friction coefficients range from 0.15 in the blankholder area, to 0.20 in the punch area. At blankholder radii and punch radii higher contact pressures and strain values are observed, consequently leading to a decrease in friction coefficients towards 0.05. The relative high friction coefficients in the blankholder area lead to a failure criteria exceeding 1.0 at the 4 corners of the product, implying that cracks might occur. A visible crack occurs at the lower left corner (red marked area), see Figure 8 (middle). The initiation of failure can also be observed from strains exceeding the Forming Limit Curve as shown in Figure 8 (right).

![Figure 8. Max failure (left), Friction distribution (middle) and Forming Limit Diagram (right)](image)

Figure 9 shows the distribution of friction coefficients and corresponding Forming Limit Diagrams for tribology systems 2 to 4. Increasing the lubrication amount from 0.6 g/m² (tribology system 1) to 2.0 g/m² (tribology system 2) only influences friction conditions in areas with relative sliding velocities higher than 50 mm/s (see the graph in Figure 7 (left)). These conditions occur in the blankholder area, reducing the friction coefficient from 0.15 to 0.14 on average, see Figure 9 (left). The decrease in friction coefficients positively influences the formability of the part as can be seen from the corresponding Forming Limit Diagram. However, as strains are within 10% distance from the Forming Limit Curve, the part is judged as critical. Reducing the roughness of the tooling from 0.4 µm (tribology system 1) to 0.2 µm (tribology system 3), result in a general decrease in friction coefficients for the complete part, see Figure 9 (middle). The reduction in friction coefficients results in a safe part without any risk of splits, although potential areas for wrinkling have been introduced in the blankholder area due to the occurrence of compressive stresses. From Figure 9 (right) it can be observed that changing the sheet coating from electrogalvanized (tribology system 1) to hot dip galvanized (tribology system 4) will also result in a general decrease in friction coefficients. A safe part is predicted with a lower risk for wrinkles compared to tribology system 3 (reduced tool roughness), as generally more stretch is introduced due to the occurrence of higher friction coefficients.
Figure 9. Distribution friction coefficients and corresponding FLD for a lubrication amount of 2.0g/m² (left), Fine polished tool surface (middle) and Hot dip galvanised coating (right)

4. Conclusions

This paper demonstrates the application of the TriboForm software to a front fender part simulated in AutoForm. In general a strong influence of tribology, friction and lubrication conditions on both the part quality and the overall production stability is observed. It is shown that the part quality of an initial critical product can be improved to a safe product by adjusting and optimizing the tribological conditions. That is, the tool roughness and sheet coating type significantly influences the final part quality, whereas the lubrication amount only influences the part quality at high punch velocities, i.e. increasing stroke rates. It is demonstrated that accounting for realistic and accurate friction and lubrication conditions improves the predicting capabilities of stamping simulations, bringing metal forming simulations to a higher level in both qualitatively and quantitatively predictions.

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