Application of an Advanced Friction Model in Hot Stamping Simulations: A Numerical and Experimental Investigation of an A-Pillar Reinforcement Panel from Volvo Cars

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Abstract. Although hot stamping is now an established method, numerical analysis of the process is still a challenge. In industrial applications, process engineers use sophisticated models which consider complex physical effects including phase transformation, phase dependent flow curves, temperature dependent r-values and temperature dependent FLC’s. However, in most of the industrial applications the tribological system is still oversimplified by using a constant Coulomb friction coefficient. Currently, there is enough experimental evidence in literature showing that friction coefficients evolve during the process, depending on contact pressure, temperature and sliding velocity. This work focuses on accurate modelling of friction in hot stamping processes. The advanced modelling technique presented in this paper tracks each material point and calculates the corresponding coefficient of friction depending on the current process conditions. This technique was used on simple part geometries in order to generate fundamental knowledge. In this analysis, part geometry, process conditions and tool kinematics are varied. In the next step, an A-Pillar reinforcement panel from Volvo Cars was analyzed experimentally and numerically. It was seen that accurate friction modelling enhances the quality of the simulation results and evolving friction conditions have a direct effect on the feasibility analysis of industrial parts.

1. Introduction
In recent years, the mass percentage of hot stamped parts in body-in-white applications increased continuously and there has been an increasing focus from researchers and software developers to simulate this process numerically [1]. Today, process engineers utilize models that consider the complex physics of the process including temperature and strain rate dependent flow curves for each phase of the steel, temperature dependent r-values, temperature dependent FLC’s, material dilatation and phase transformation models. Although such sophisticated models are used, the friction conditions are still oversimplified by using constant Coulomb friction coefficient in most of the industrial applications. This
is mainly due to the lack of experimental investigations and due to lack of an effective tool to consider the findings of the researchers [2].

In direct hot stamping process usually an AlSi coating is used. As the blank is heated in the furnace, intermetallic compounds are formed by diffusion of Al, Si and Fe which leads to a multi-layered structure with approximately 40 μm thickness on the blank surface [3]. The coating fractures during forming mainly due to thermo-mechanical loads and the fractured debris initiates tool wear which has a strong effect on tribological state [4]. A constant Coulomb friction coefficient in finite element simulations simplifies the complex tribological behavior and reduces the multi-dimensional friction coefficient to a “single constant number”. However, there is experimental evidence that the friction coefficient is not constant in case of AlSi coatings [5,6]. Studies about friction mechanism of AlSi coating consider mostly adhesion and ploughing effects. Ghiotti et al. analyzed the tribological behavior of the coating by using pin on disc test at different temperatures and contact pressures and found that with increasing contact pressure the friction coefficient decreases [7]. With increasing temperature, the shear strength of the coating is reduced and therefore the friction coefficient also decreases. Most of the modeling and characterization effort in literature mainly consider the global friction coefficient on a macro level [8]. However, contact conditions and surface topography play an important role in friction. In other words, friction is a multi-scale problem. It has been shown for cold forming that advanced modeling of friction increases the quality of finite element simulations [9].

In this work, multi-scale friction modelling was applied to hot stamping of manganese boron steels with AlSi coating. In the following sections, the modeling strategy will be introduced and applied to basic part geometries to obtain fundamental understanding of the effect of friction in hot stamping. Afterwards, the strategy will be applied to an industrial part: an A-pillar reinforcement from Volvo Cars. The focus here is the comparison between advanced modeling and simple Coulomb modelling as a function of different process parameters.

2. Advanced Friction Model
The TriboForm software allows for multi-scale modelling of friction coefficient. Friction models are constructed using physically-based mathematical models considering a wide range of process conditions [10]. The tribology system information as described in the next section, combined with the actual 3D surface topographies of the sheet and tools, enables the generation of a TriboForm Library. The experimental data for the calibration process as described in [10] is obtained via experiments performed at Tata Steel [11]. A full description of the mathematical models, experimental set-up and calibration procedure of required input parameters are described by Venema in [3]. The resulting TriboForm friction models can be imported in the AutoForm software using the TriboForm FEM Plug-In (Figure 1).

![Advanced friction modelling approach in hot stamping simulations](image)

2.1. Tribological system
The sheet material used in this paper is a 22MnB5 Boron steel with an Al-Si coating. To fully define the tribological system, the 3D surface topographies of both the sheet and tools are required. In order to capture the 3D surface topography of the sheet, the sheet was heated to a temperature of 930°C to activate the diffusion process of the coating, and cooled down to perform 3D confocal measurements. Due to the diffusion process a multi-layer coating structure is formed with a roughness generally higher
than the original surface topography. The forming dies are constructed of high performance Orvar Supreme tool steel, having an assumed average surface roughness (Sa) ranging from 0.6μm to 1.0μm (see Figure 2), which are typical roughness values of production dies [9].

Figure 2. Surface topographies of 22MnB5 and tool surface

2.2. Simulation of friction conditions
Friction conditions are simulated by loading and sliding the tool surface onto the sheet surface, see Figure 3 (left). The resistance between sliding surfaces are introduced by the plastic deformation and fracture of the coating layer and ploughing and adhesion effects between the tool surface asperities and sheet surface asperities. In Figure 3 (right) pressure and temperature dependent friction coefficients are shown for a tool surface roughness of 0.6 μm and 1.0 μm, respectively. The friction model was constructed for a contact pressure ranging from 1-30 MPa, an equivalent plastic strain range from 0-0.4, a velocity range from 1-300 mm/s and an interface temperature range from 450-750 °C. From Figure 3 (right) it can be seen that friction coefficients decrease with increasing contact pressures. Also, the friction coefficient decreases with increasing temperatures between 400 °C and 600 °C, and increases for temperatures exceeding 600 °C. The pressure and temperature dependent trends captured by the advanced friction model corresponds to the observations of a number of researchers [12,13], and can be explained by a number of phenomena that can interact in contradictory manner, i.e. softening of the sheet material due to elevated temperatures, change in adhesive bonds between sheet and tool and the occurrence of abrasive and adhesive galling.

Figure 3. a) Contact of tool and sheet and b) friction coefficients

2.3. Modelling of hot stamping process
The hot stamping simulations are performed by using AutoForm R8 in conjunction with the TriboForm FEM Plug-In for AutoForm to describe tribological conditions. In all simulations elastic-plastic shell elements were used having 11 integration points across the thickness. The tools were modelled as rigid.
The hardening behaviour was modelled based on temperature, strain rate and phase-dependent flow curves which means that each of the phases bainite, ferrite-pearlite, martensite and austenite is described by separate hardening curves. The phase transformation is calculated using a model that contains the information from the isothermal and continuous cooling TTT diagrams [14]. In order to model the effect of plastic strain on critical cooling rates, TTT information with pre-strain is also included. Phase dependent dilatation information is used to model the volume change precisely, which has a direct influence on the blank size and thermal distortion. The heat transfer between the tools and the sheet metal is modelled using pressure and gap-dependent heat transfer coefficients. The processes were modelled on the basis of the entire process chain: heating the blank in the furnace, transport to the press, positioning the blank on the tools, forming, quenching, opening of the tools and cooling to room temperature. The basic part simulations were modelled by using constant tool temperatures. In the final section, tools are modelled with 3D heat conduction considering the cooling channels.

3. Analysis with basic part geometries

The main aim here is to understand the effect of advanced friction modelling as compared to using constant Coulomb friction. There are two questions to be answered: how large is the difference between simulations using these two models and what is the effect of part geometry and process parameters on this difference? As a measure to compare simulations, the thinning results are used, which are expressed as engineering strain in thickness direction and given in percent.

![Comparison of thinning results obtained by different friction modelling methods](image)

**Figure 4:** Comparison of thinning results obtained by different friction modelling methods
Figure 4 presents used geometries and the maximum thinning values obtained by using constant Coulomb friction and an advanced friction model utilizing a sheet thickness of 1.5 mm, furnace temperature of 925 °C, 7.5 s transport time, 1 mm binder gap and a forming velocity of 200 mm/s. The results are given for a die radius of 10 mm and 30 mm. Starting from a simple rail geometry, the complexity of the parts are increased gradually. The rail part (first row) is insensitive to the used friction model because the achieved thinning is very low. The flange of the part has a one sided contact due to the binder gap and this prevents the parts to be stretched. Circular cup (second row) is very sensitive to the used friction model. In the case of smaller die radius, the Coulomb model is more critical and in the case of larger die radius the advanced friction model is more critical. This is mainly due to the contact pressure in the radius regions. Sharp radius generates more contact pressure and under high pressure the sheet surface gets smoother. This leads to a decrease in coefficient of friction in case of advanced friction modelling. High contact pressure means also a faster loss of heat to the tools and colder material in those regions leads also to less friction coefficient. The results with the square cup (third row) are similar to the circular cup case. However, the difference between the models is less compared to the circular cup. It is seen that the deformation is concentrated on the corners in this case, where the contact pressures are rather high, independent of the die radius. Combined circular cup (fourth row) is a combination of two circular cups with different radii. The part has also straight edges and concave surfaces. Also in this part, it is seen that the advanced friction model predicts less thinning in case of smaller die radius, which is similar to the circular cup case. Combined rectangular cup (last row) represents a combination of two square cups. As in the case of square cup, it is seen here again that the difference between the models is reduced as compared to the combined circular cup. Here the localized contact pressure is governing the development of the friction coefficients and also the thinning results. The main outcome here is that the advanced friction model can provide less critical or more critical thinning results depending on the part geometry. The die radius is the dominant parameter in terms of friction. The part radius (circular vs. rectangular geometry) has a secondary effect which changes the difference between the models.

In another step, some process parameters (ram velocity, furnace temperature, transfer time) and material thickness are varied in selected geometries. Figure 5 presents the thinning results for the combined rectangular shape with a die radius of 30 mm. The results are evaluated on the marked corner. It is seen that the material thickness is affecting the friction sensitivity of the part. For higher thicknesses, it is less important which friction model is used. Both cases provide the same result. For thinner materials, the parts get more friction sensitive and the differences between the two models gets larger. A similar trend can also be seen for the blank temperature. In case of colder blanks, the difference between the models is 3 %. However with the higher blank temperatures the difference increases to 12 %. This is mainly due to the temperature dependency of the advanced friction modelling technique. Especially, in high temperatures and less contact pressures, the friction coefficients tend to be very high as compared to the constant model. The ram velocity does not directly affect the frictional behaviour of the parts. It has a rather indirect effect. With higher velocities the part does not lose much heat to the tools due to less contact times. Therefore, it affects the friction over the temperature effect indirectly.

![Figure 5: Effect of a) material thickness and b) blank temperature after transport](image-url)
4. Application to an A-Pillar reinforcement

In order to apply the generated knowledge, an A-Pillar lower reinforcement part from Volvo Cars was studied. This part is known to be sensitive to friction. A gap controlled binder is used in this process and according to former production experience the formability on the critical corner is highly dependent on the used gap value. In the finite element analyses, cyclic simulations considering the cooling channels were utilized to calculate the 3D heat conduction in the tool volumes. This leads to a more accurate surface temperature calculation.

In order to analyze the effect of advanced friction modeling on simulation accuracy, thickness measurements were performed around the critical zone of the part. The comparison of measured and simulated thickness values obtained by using different friction models can be seen in Figure 6. With a constant Coulomb friction coefficient of 0.45 the difference between the numerical and experimental thickness is about 5% (Figure 6.a). In the case of advanced friction model, two different cases were investigated. In the first case, an average tool roughness value (Sa) of 0.6 μm was used. The results show that the thickness predictions are enhanced in most of the measurement points (Figure 6.b). The model predicts less thinning in a large portion of the corner region. The only difference between these simulations is the friction modelling technique (Figure 6.a-b). Hence, the change in the thickness distribution is only due to friction conditions.

In the second case with a tool roughness of 1.0 μm a higher friction coefficient is expected. As a result, this leads to more thinning in the material (Figure 6.c) which can be seen in all of the measurement points. This shows the impact of advanced friction modelling: The model does not only depend on temperature, contact pressure and sliding velocity but also considers the actual surface topographies of both the blank and tools.

Another impact of advanced friction modelling is seen in the effect of the used binder gap. In the production, binder gap is optimized in order to optimize the thinning in the material. The gap between the binder and the die has a direct effect on the observed thinning distribution. If a gap size of 1.2 and 3.0 mm are used, a considerable change in the thinning predictions should be expected in the numerical simulations. However, this is not the case using a constant Coulomb coefficient of friction as seen in Figure 7.a. The thinning decreases in all of the points, but, the decrease is only around 1%. Moreover, the thinning distribution around the corner region is very similar.
When the advanced friction model is used, we observe that the thinning decreases considerably with the increased gap value (Figure 7). The nominal change in thinning is about 3% in some of the points. It can be observed that the critical region around the corner becomes less critical. This means that the expected effect of changing the gap values can be simulated more realistically when we consider an advanced friction model in finite element simulations.

Figure 7: Numerical thinning results with advanced friction model for binder gaps of a) 1.2 mm and b) 3.0 mm

The main result of advanced friction modelling can be seen in Figure 8 where the calculated friction coefficients are presented on surfaces in contact with the die (die side) and with the punch (punch side) at two different drawing depths. It is seen that friction coefficient is not constant on the part surface having a variation between 0.2 and 0.9 depending on the temperature, velocity and contact pressure. Generally, around the small die radii, lower friction coefficient values around 0.25 are observed. This is mainly due to high contact pressures and low temperatures on those regions. On the flange and flat surfaces, larger friction coefficients are calculated. This is mainly due to low contact pressures.

Figure 8: Calculated friction coefficient distribution on the top and bottom surfaces of the part
5. Conclusion
In industrial applications, the friction coefficient in hot stamping processes is still considered to be constant. The main reason behind this is the lack of an efficient tool to model the complex tribological system accurately. In this paper, an advanced friction modelling technique is introduced for hot stamping. The model calculates friction coefficients based on surface topography, temperature, sliding velocity, plastic strain and contact pressure. Application of this technique to basic part geometries revealed that the differences in thinning results between constant Coulomb friction and advanced friction modelling can be more than 25%. Especially the part radii, the base radii, blank temperature and material thickness affect these differences considerably. Application of the method to an A-pillar reinforcement part shows that advanced friction modelling improves the thickness prediction of numerical simulations. Moreover, the effect of binder gap can be analyzed accurately with this strategy as compared to constant Coulomb model which oversimplifies the problem. As a result, the physics of the tribological system is included in a friction model dedicated to AlSi coated manganese boron steels and the process engineers in the industry can use this advanced friction modelling approach directly without any additional effort.

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