MULTISCALE FRICTION MODELING FOR SHEET METAL FORMING

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Abstract

The most often used friction model for sheet metal forming simulations is the relative simple Coulomb friction model. This paper presents a more advanced friction model for large scale forming simulations based on the surface change on the micro-scale. The surface texture of a material changes when two surfaces are in contact under a normal load. This is caused by flattening due to combined normal loading and stretching. The consequence of this is that shear stresses between the contacting surfaces, developed by adhesion and ploughing effects between contacting asperities, will change when the surface texture changes. A numerical procedure has been developed which accounts for the change of the surface texture on the micro-scale and its influence on the friction behavior on the macro-scale. The numerical procedure is implemented in a finite element code and applied to a full scale sheet metal forming simulation.

Keywords**:** friction mechanisms, asperity contact, flattening, real contact area, ploughing, adhesion

1 INTRODUCTION

The automotive industry uses Finite Element (FE) software for formability analyses to reduce the cost and lead time of new vehicle programs. In this respect, FE analysis serves as a stepping stone to optimize manufacturing processes. An accurate forming analysis of an automotive part can however only be made if, amongst others, the material behavior and friction conditions are modeled accurately. For material models, significant improvements have been made in the last decades, but in the majority of simulations still a simple Coulomb friction model is used. The Coulomb friction model does not include the influence of important parameters such as pressure, punch speed or deformation of the sheet material. Consequently, even using the latest material models, it is still cumbersome to predict the draw-in of a blank during the forming process correctly.

To better understand contact and friction conditions during lubricated sheet metal forming (SMF) processes, experimental and theoretical studies have been performed in order to describe microscopic dependencies. On microscopic level, friction is due to adhesion between contacting asperities [1,2], the ploughing effect between asperities [1,2] and the appearance of hydrodynamic friction stresses [3,4]. Ploughing effects between asperities and adhesion effects between boundary layers are the main factors causing friction in the boundary lubrication regime. If the contact pressure is carried by the asperities and the lubricant flow, as in the mixed- and hydrodynamic lubrication regime, hydrodynamic shear stresses will become important. This paper will focus on the friction mechanisms present in the boundary layer regime: ploughing and adhesion.

Wilson [1] developed a friction model which treated the effect of adhesion and ploughing separately. A more advanced friction model is developed by Challen & Oxley [2] which takes the combining effect of ploughing and adhesion on the coefficient of friction into account. Their friction model assumes contact between a ‘hard’ wedge-shaped asperity and a ‘soft’ flat material. Westeneng [5] extended the model of Challen & Oxley to describe friction conditions between a flat workpiece material and multiple, spherical shaped, tool asperities. His model considers the flattened plateaus of the workpiece asperities as soft and perfectly flat and the surface texture of the tool as hard and rough.

The influence of ploughing and adhesion on the coefficient of friction depends on the real area of contact. The coefficient of friction will change if the real area of contact changes. The real area of contact depends on different flattening and roughening mechanisms of the deforming asperities. The three dominating flattening mechanisms during SMF processes are flattening due to normal loading [6], flattening due to stretching [7,8] and flattening due to sliding [9]. Flattening increases the real area of contact representing a higher coefficient of friction. Roughening of asperities, observed during stretching the deformed material [10], tends to decrease the real area of contact resulting in a lower coefficient of friction. The two mechanisms outlined in this paper are flattening due to normal loading and flattening due to stretching.

A large research area within the field of friction modeling is focused on developing models to predict the flattening behavior of asperities due to normal loading. Most of these models are based on the pioneering work of Greenwood & Williamson [6] which developed a stochastic model based on contact between a flat tool and rough workpiece surface. Over the past decades, modifications have been made to this model to account for arbitrary shaped asperities, plastically deforming asperities and the interaction between asperities. Westeneng [5] derived an ideal plastic and nonlinear plastic contact model based on the conservation of volume and energy and the assumption that displaced material reappears as a uniform rise in the non-contacting surface. Westeneng modeled the asperities by bars which can represent arbitrarily shaped asperities. The models include a persistence parameter, work hardening parameters and are able to describe the interaction between asperities.

A further increase of the real area of contact could occur if during normal loading a bulk strain is applied to the material. The effective hardness of the asperities can be largely reduced if a bulk strain is present in the underlying material [7]. Westeneng [5] developed a strain model which describes the influence of strain on a surface geometry with arbitrary shaped asperities. The model is applicable to both plane strain and plane stress situations dependent on the definition of the non-dimensional strain rate [5].

In this paper, a numerical procedure is proposed which couples the different friction mechanisms. A general overview of the numerical procedure is presented and the translation from micro to macro modeling is outlined. The development of the real area of contact is described by the flattening models proposed by Westeneng [5] and the effect of ploughing and adhesion on the coefficient of friction is described by the modified friction model of Challen & Oxley [5]. The numerical procedure has been applied to a full scale sheet metal forming simulation which shows the applicability of the numerical procedure.

2 THEORETICAL BACKGROUND

2.1 NUMERICAL PROCEDURE

A numerical procedure, to be used in finite element codes, has been developed to couple the different micro friction models. The numerical procedure starts with defining the process variables and material characteristics. Process variables are the nominal contact pressure and strain in the material which are calculated by the FE code. The contact pressure carried by the asperities equals the total nominal contact pressure since hydrodynamic friction stresses will be neglected. Material characteristics are the hardness of the asperities and the surface properties of the tool and workpiece material. Once the input parameters are known, the real area of contact is calculated based on flattening due to normal loading and flattening due to stretching. The amount of indentation of the harder tool asperities into the softer workpiece asperities can be calculated if the real area of contact and the contact pressure carried by the asperities are known. After that, shear stresses due to ploughing and adhesion effects between asperities and the coefficient of friction are being calculated.

Friction models encompassing micro mechanisms are generally regarded as too cumbersome to be used in large scale FE simulations. Translation techniques are therefore necessary to translate microscopic behavior to macroscopic behavior. Using stochastic methods, rough surfaces are described on micro-scale by their statistical parameters (mean radius of asperities, asperity density and the surface height distribution). Assuming that the surface height distribution on the micro scale represents the surface texture on the macro scale, it is even possible to describe contact problems between tool and workpiece of large scale FE problems [5].

Statistical parameters can be used under the assumption that the surface texture is isotropic and can be represented by 2-dimensional random noise. It is assumed that these restrictions are true for the workpiece and tool material which makes the use of statistical parameters favorable to make the translation from micro to macro modeling.

2.2 CHARACTERIZATION OF ROUGH SURFACES

The surface height distribution of the tool and workpiece material is obtained from the surface profiles of the rough surfaces (Fig. 1). A discrete surface height distribution will be obtained which has to be evaluated by a continuous function. A continuous function is required to eliminate the need of integrating discrete functions during the numerical procedure.

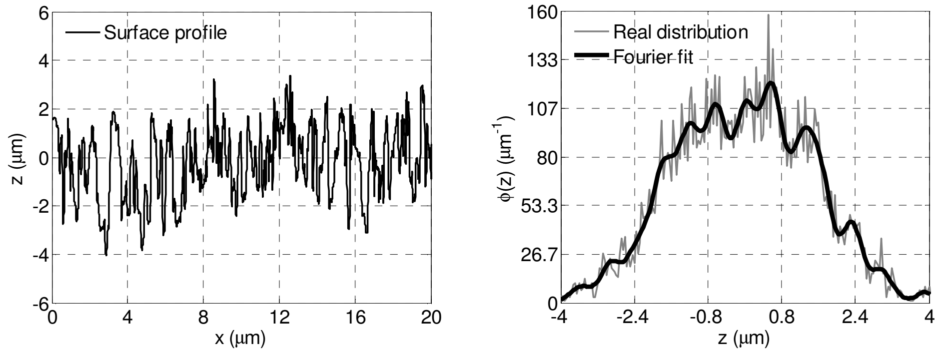

Figure 1: Surface profile (left) and corresponding surface height distribution (right)

An advanced method to describe discrete signals is by using Fourier series. Fourier series makes it possible to describe non-smooth asymmetric distribution functions from which the accuracy of the evaluation depends on the number of expansions used.

The results discussed in this paper are obtained by evaluating the surface height distribution functions by a half range sine Fourier function, given by:

$$f_{Fourier}(x) = \sum_{n=1}^{\infty} b_n \sin\left(\frac{n\pi}{L}x\right) \qquad \text{with} \qquad b_n = \frac{2}{L}\int_0^L f(x)\sin\left(\frac{n\pi}{L}x\right)dx \qquad (1)$$

with n the number of expansions and L the evaluation domain. In Figure 1, the measured surface height distribution from the workpiece material is evaluated by a Fourier function using 15 expansions.

2.3 FLATTENING MECHANISMS

Two flattening mechanisms have been implemented in the numerical procedure to calculate the real area of contact of the workpiece: flattening due to normal loading and flattening due to stretching. The models of Westeneng are used for this purpose [5]. Westeneng modeled the asperities of the rough surface by bars which can represent arbitrarily shaped asperities, Figure 2.

Westeneng introduced 3 stochastic variables as presented in Figure 2: The normalized surface height distribution function of the asperities of the rough surface $\phi(z)$, the uniform rise of the non-contacting surface U (volume conservation) and the separation between the tool surface and the mean plane of the asperities of the rough surface d.

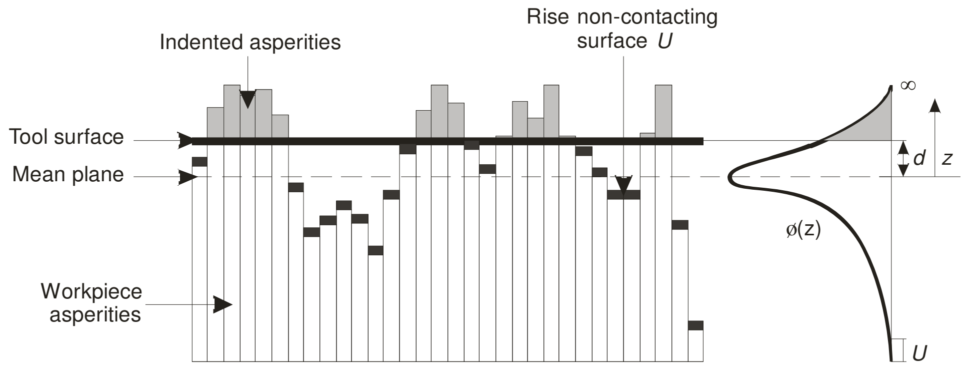

Figure 2: A rough soft surface indented by a smooth rigid surface

Using the normalized surface height distribution $\phi(z)$, the amount of flattening of the contacting asperities d and the rise of the non-contacting asperities U can be calculated by solving the following set of equations:

$$0 = \xi\left(1 + \eta \frac{\int_{d}^{\infty}(z-d)\phi(z)dz}{\int_{d-U}^{d}(z+U-d)\phi(z)dz + \int_{d}^{\infty}(z-d)\phi(z)dz}\right) - \frac{p_{nom}}{H} \tag{2}$$

$$0 = \int_{d-U}^{\infty}(z+U-d)\phi(z)dz - U \tag{3}$$

In which H represents the hardness of the softer material (in MPa), η is the persistence parameter (energy required to lift up the valleys) and ξ is a parameter which characterizes the ideal plastic contact model. The value of the parameter η is bounded between 0 (no energy needed to raise the valleys) and 1 (maximum amount of energy required to raise the valleys). In this paper, the value of η is taken equal to p_{nom}/H resulting in an increasing persistence parameter for increasing load [5]. The parameter ξ can be determined by equation 4:

$$\xi = \frac{\left(\int_{d-U}^{d}(z+U-d)^{n}\phi(z)dz + \int_{d}^{\infty}(z-d)^{n}\phi(z)dz\right)}{\left(\int_{d-U}^{d}(z+U-d)^{n+1}\phi(z)dz + \int_{d}^{\infty}(z-d)^{n+1}\phi(z)dz\right)} \tag{4}$$

in which n represent an indentation parameter. For indented bars which deform ideal-plastically it is expected that the value of n is close to one [5].

The ratio of real to apparent area of contact α can be found by equation 5 once the amount of indentation d and rise of the valleys U are calculated from equation 2, 3 and 4:

$$\alpha = \frac{A_r}{A_{nom}} = \int_{d-U}^{\infty} \phi(z) dz \tag{5}$$

An extensive research on the influence of the parameters η and n on the real area of contact, amount of indentation and rise of the valleys can be found in [5].

Besides an ideal-plastic contact model for normal loading, Westeneng derived an analytical contact model which describes the influence of strain on deforming, arbitrary shaped, asperities. The hardness of the deforming asperities will decrease due to stretching of the material resulting in a higher amount of indentation of the contacting asperities d_s and rise of the non-contacting asperities U_s. The subscript s corresponds to the influence of strain on the parameters d and U found by the ideal plastic contact model for normal loading. Values for α, d_s and U_s can be found by an iterative solution scheme, see Figure 3.

The parameter l in Figure 3 represents half the asperity distance and can be obtained from equation 6 with Q representing the asperity density of the workpiece. The non-dimensional strain rate E is described by Wilson & Sheu [7] for a plane stress deformation mode and by Sutcliffe [8] for a plane strain deformation mode.

$$l = \frac{1}{2\sqrt{Q\alpha}} \tag{6}$$

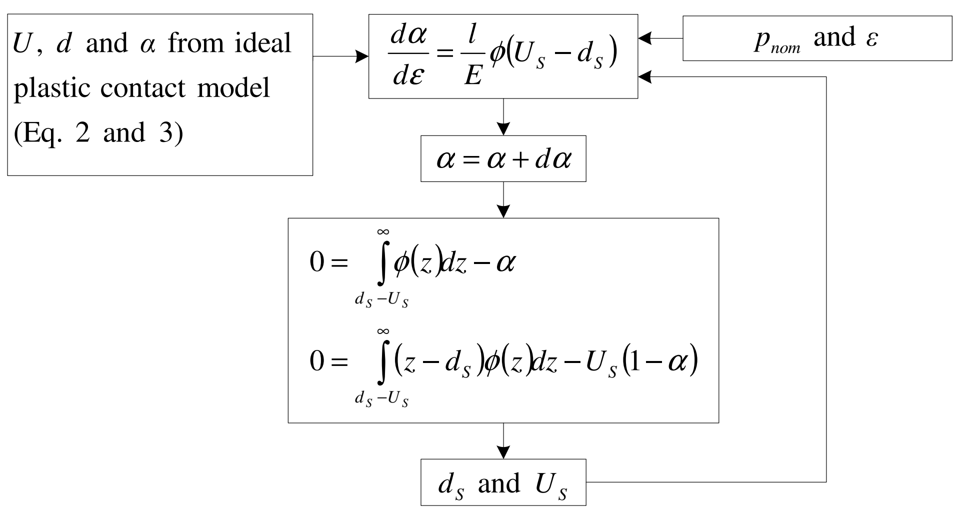

Figure 3: Calculation scheme for strain contact model

2.4 SHEAR STRESSES

The friction model of Challen & Oxley [2] takes the combining effect of ploughing and adhesion effects between wedge-shaped tool asperities and flat workpiece asperities into account. Westeneng [5] extended the model of Challen & Oxley to describe friction conditions between a flat workpiece material and multiple, spherical-shaped tool asperities, Figure 4. This 'modified' friction model of Challen & Oxley has been implemented in the numerical procedure to describe friction conditions between the tool and workpiece material.

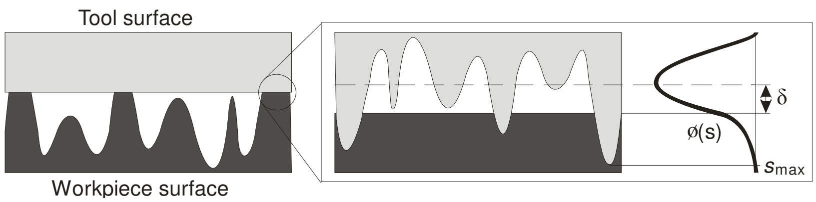

Figure 4: Indentation tool asperities

Westeneng describes the translation from friction forces occurring at single asperity contacts to the total friction force at multiple asperities by:

$$F_w = \rho_t \alpha A_{nom} \int_{\delta}^{s_{max}} F_{w,asp} \phi_t(s) ds \quad (7)$$

In which ρ_t represents the asperity density of the tool surface, α the ratio of real to apparent area of contact of the workpiece, A_{nom} the nominal contact area, ϕ_t the normalized surface height distribution function of the tool surface and $F_{w,asp}$ the friction force occurring at one single asperity. The friction force $F_{w,asp}$ is described by Challen & Oxley [2] for wedge-shaped asperities and Westeneng [5] for spherical shaped asperities. The bounds of the integral are described by s_{max}, the maximum height of the tool asperities, and δ, the separation between the workpiece surface and the mean plane of the tool asperities (Fig. 4). The amount of separation δ can be calculated based on force equilibrium by solving the equation:

$$0 = \left(\pi \beta_t \rho_t \int_{\delta}^{s_{max}} (s - \delta) \phi_t(s) ds \right) \alpha A_{nom} H - p_{nom} A_{nom} \quad (8)$$

The term between brackets represents the ratio of real to apparent area of contact of the tool asperities penetrating into the workpiece material and β_t is the mean radius of the tool asperities.

If the shear stresses are known from Equation 7 the coefficient of friction can be calculated by equation 9:

$$\mu = \frac{F_{w,asp}}{F_N} \quad (9)$$

3 RESULTS

The numerical procedure to determine the friction coefficient is tested in a simulation of the cross-die product (Fig. 5). The cross-die product is a test product designed by Renault which approximates process conditions of complex automotive parts. Simulations are performed using the in house FE code Dieka, developed at the University of Twente.

Due to symmetry of the cross-die product only a quarter of the workpiece was modeled. The workpiece was meshed by 9000 triangular discrete Kirchhoff shell elements using 3 integration points in plane and 5 integration points in thickness direction. The yield surface was described by the Vegter model [11] using the Bergström–Van Liempt hardening relation [12] to describe hardening behavior. Material parameters were used from DC04 low carbon steel, a typical forming steel used for SMF processes. Contact between the tools and the workpiece was described by a penalty method using a penalty stiffness of 200 N/mm. The coefficient of friction used in the contact algorithm was calculated based on the numerical procedure presented in this paper. Models to describe flattening due to normal loading and flattening due to stretching were included to determine ploughing and adhesion effects between contacting asperities. The simulation was performed by prescribing the displacement of the punch until a total displacement of 60 mm was reached. The punch speed was set to 6 cm/sec and the applied blankholder force was 61 kN.

Two simulations have been performed in order to show the individual contribution of the two flattening mechanisms. The first simulation only describes the influence of normal loading on the coefficient of friction, Figure 5. The second simulation used both flattening models to describe the development of the coefficient of friction, Figure 6. Both figures show higher contact ratios and friction coefficients in areas where higher strains and contact pressures occur.

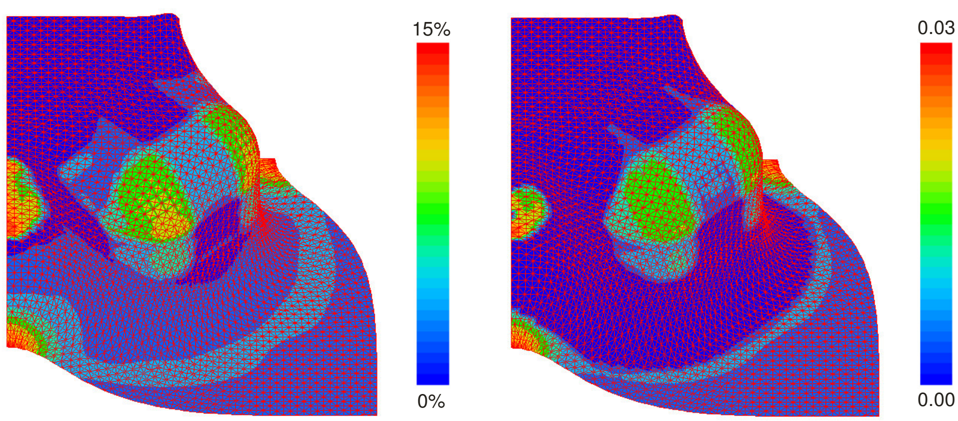

Figure 5: Development real area of contact (left) and coefficient of friction (right) for normal loading only

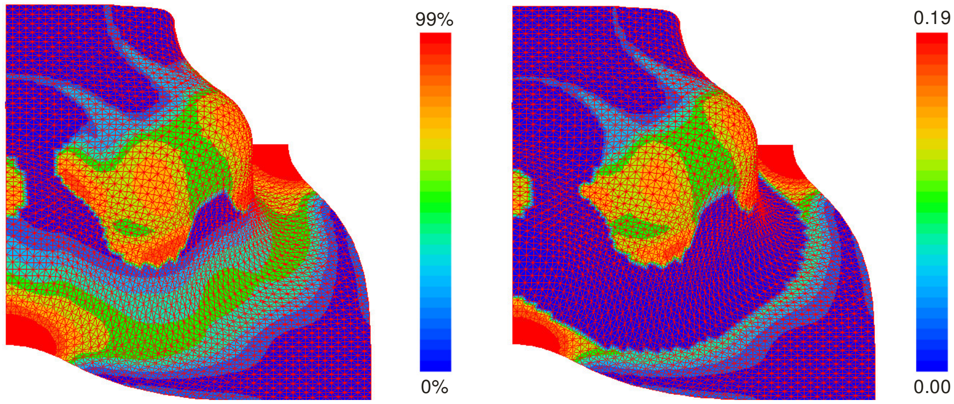

Figure 6: Development ratio of real to apparent area of contact (left) and coefficient of friction (right) for normal loading + stretching

If only flattening due to static loading is assumed (Fig. 5), rather low values for the real area of contact are obtained resulting in low values for the coefficient of friction. This result is questionable, but it should be noticed that only one flattening mechanisms has been taken into account during the simulation. If the second flattening mechanism is taken into account (flattening due to stretching) much higher values for the real area of contact are obtained (Fig. 6). The higher amount of contact ratios results in higher values of the coefficient of friction which eventually leads to a friction distribution lying within the range of expectation. Expected values of the coefficient of friction are found in regions where high strains and contact pressures occur and low values of the coefficient of friction are obtained in low pressure regimes.

4 CONCLUSIONS

This paper presents a numerical procedure to calculate the coefficient of friction during large scale FE simulations. The numerical procedure includes two flattening mechanisms to describe the real area of contact, a friction model including ploughing and adhesion effects to calculate the coefficient of friction and statistical parameters to make the translation from micro- to macro modeling. The numerical procedure has been applied to a full scale sheet metal forming simulation which shows the applicability of the developed algorithm. Results of the simulations have shown that relatively low values of the coefficient of friction are found in case of normal loading only, the first flattening mechanism. If a second flattening mechanism is applied, flattening due to stretching, much more promising results are obtained.

Besides the friction mechanisms discussed in this paper, other mechanisms exist which are expected to have a large influence on the real area of contact and coefficient of friction. The influence of sliding and roughening due to stretching on the real area of contact should not be neglected, as well as hydrodynamic friction stresses occurring in the mixed lubrication regime. Therefore more research is required to include these dependencies into the numerical procedure to obtain a reliable and accurate multi-scale friction model.

5 ACKNOWLEDGMENTS

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