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Numerical simulation of friction in metal forming using a halfspace model

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Abstract. Sheet and bulk metal forming are widely used manufacturing methods. The industrial trend towards function integration leads to a demand for workpieces having features of both methods. The new forming technology sheet-bulk metal forming is a promising approach to manufacture workpieces with functional elements. Tribological aspects generally play an important role in metal forming processes. Especially for the formability of functional elements friction is very important. The coexistence of low and high contact pressures is characteristic of sheet-bulk metal forming and presents a challenge for the friction modelling. The surfaces of tool and workpiece are always rough, so that initial contact only occurs at the asperities of surface roughness. Consequently for small and moderate loads the real contact area is smaller than the apparent contact area. Surface traction can only occur in the real contact area, so that it is necessary to determine the real contact area in order to study the tribological behaviour of contact pairs. In order to get an accurate determination of the real contact area it is necessary to calculate the surface deformation in a three-dimensional model and to validate the simulation model by measurements. The halfspace approach has the significant advantage that only the surface has to be discretised, while in a Finite Element Analysis the whole bulk has to be discretised. Consequently the numerical effort, and thus the calculation time, in the halfspace model are much lower than in FE-modelling. The numerical solution scheme based on the halfspace theory is presented in this paper. Results of the calculation of the real contact area of rough surfaces are compared to experimental data from ultrasonic inspection. Friction coefficients calculated with the halfspace model are compared to results of strip drawing tests.

Keywords: Simulation, halfspace model, friction, metal forming, real contact area, ultrasonic inspection, strip drawing

PACS: 46.55.+d

INTRODUCTION

Sheet and bulk metal forming are widely used manufacturing methods. They allow the economic mass-production of workpieces because of their high material efficiency and short process times. The industrial trend towards function integration leads to a demand for workpieces having features of both methods. A promising approach to satisfy this demand is the direct forming of high precision workpieces with functional elements starting from blanks. Thus classical sheet metal forming operations such as deep drawing have to be combined with bulk metal forming operations like extrusion. This new forming operation called sheet-bulk metal forming allows the forming of complex workpieces with functional elements, like for example teeth.

Tribological aspects generally play an important role in metal forming processes and have a significant influence on tool life and dimensional accuracy of workpieces. Especially for the forming of functional elements friction is very important. The coexistence of low and high contact pressures is characteristic of sheet-bulk metal forming and presents a challenge for the friction modelling.

The surfaces of tools and workpieces are always rough, so that initial contact only occurs at the asperities of surface roughness. Consequently for small and moderate loads the real contact area A_{real} is smaller than the apparent contact area A_o and approaches A_o only for very high contact pressures. Surface traction can only occur in A_{real} , so that it is necessary to determine A_{real} in order to study the tribological behaviour of contact pairs.

Real rough surfaces show fractal properties for small scales, which means that roughness with large wavelength is superimposed with roughness of smaller wavelength. Archard [1] showed that, if purely elastic deformation and spherical shape of asperities is assumed, the relationship between the normal force and the real contact area approaches a linear dependency when more and more wavelengths are taken into account. Bowden and Tabor [2] state that due to the small initial real contact area the pressure at the surface is locally very high, so that local plastification of the surface occurs even for small contact loads. The relation between the average contact pressure P and the real contact

area is then given by:

$$\frac{P}{H} = \frac{A_{real}}{A_o} \quad (1)$$

The surface hardness H is the contact pressure which leads to plastic surface deformation. It was experimentally identified to be approximately three times the yield stress of the softer contact partner. However it was shown by Pullen and Williamson [3] that the contact pressure can reach higher values when material flow normal to the contact direction is inhibited.

The results of Archard and Bowden and Tabor lead to linear relations between contact pressure and real contact area, which is in accordance with the Coulomb friction law. However, Pullen and Williamson found a nonlinear relationship. In order to get an improved determination of the real contact area it is necessary to calculate the surface deformation in a three-dimensional model and to validate the simulation model by measurements. Unfortunately the multiscale character of real rough surfaces makes the simulation of large surfaces in high resolution necessary. This leads to a large number of surface points in the simulation model. The halfspace approach has the significant advantage that only the surface has to be discretised, while in a Finite Element Analysis the whole bulk has to be discretised. Consequently the numerical effort, and thus the calculation time, in the halfspace model is much lower than in FE-modelling.

HALFSPACE MODEL

A halfspace is an infinite space which is limited in one direction by a surface. In the halfspace model the contact of the halfspace surface with a rigid and perfectly flat plane is analysed. The surface height $h(x, y)$ is the sum of the surface heights of tool and workpiece. The local geometrical interference $\bar{u}_z$ is defined as (see figure 1a)

$$\bar{u}_z = h(x, y) - (h_{max} - d) \quad (2)$$

Where h_{max} is the maximum surface height and d is the approach in normal direction of the surfaces. Since a geometrical interference of solid bodies is impossible $\bar{u}_z$ equals the composite surface deformation of the contact partners in the real contact area (prescribed displacement). The displacement of a surface point $u_z(x, y)$ due to a surface pressure $p(\xi, \eta)$ can be calculated by using the Boussinesq solution [5]

$$u_z(x, y) = \frac{1}{\pi E^*} \int_{\Gamma} \frac{p(\xi, \eta)}{\rho} d\Gamma \quad (3)$$

In order to account for the compliance of both contact partners the composite elastic modulus E^* is used here

$$\frac{1}{E^*} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \quad (4)$$

E_i and ν_i are the Young's moduli and Poisson's ratios of the contact partners. The distance ρ between the position of the load (x_l, y_l) and the position of the calculated displacement (x_k, y_k) is given as

$$\rho = \sqrt{(x_k - x_l)^2 + (y_k + y_l)^2} \quad (5)$$

FIGURE 1. Surface displacement (a) and discretisation (b) in the halfspace model

The surface is discretised into rectangular elements of size $2a \times 2b$. When the pressure is assumed constant on the elements, equation (3) can be written as

$$u_{zk} = \sum_{l=1}^M C_{kl}^{(zz)} p_l \quad (6)$$

The deformation u_{zk} in z -direction at element k is now given as the summation of the product of the compliance matrix $C_{kl}^{(zz)}$ times the pressure p_l at element l over all M elements in contact. The compliance matrix is defined as

$$C_{kl}^{(zz)} = \frac{1}{\pi E^*} \int_{-a}^a \int_{-b}^b \frac{1}{\rho_{kl}} d\eta d\xi \quad (7)$$

where ρ_{kl} is now

$$\rho_{kl} = \sqrt{(x_k - x_l - \xi)^2 + (y_k - y_l - \eta)^2} \quad (8)$$

The solution to the contact problem is based on a variational principle. The pressure distribution and the real contact area are determined by minimisation of the total complementary potential energy of the system. This method is explained in detail by Tian and Bhushan [4] and leads to the following system of equations

$$\sum_{k=1}^M C_{kl}^{(zz)} p_l - \bar{u}_z = 0 \quad \implies \quad C^{(zz)} p = u_z \quad (9)$$

This linear system of equations is solved iteratively using the Gauss-Seidel method. Due to the fact that tensions are impossible in the contact zone the pressure field has to be forced to contain no negative elements

$$p_l \geq 0 \quad l = 1, \dots, M \quad (10)$$

After the elastic contact simulation the pressure field is checked for pressure values p which are higher than the surface hardness H . Where such high pressures occur the surface height is reduced locally by the plastic deformation increment Δu_{zp} . This leads to a reduction of pressure peaks by enlarging the real contact area. Δp is the difference between p_l and H at all the patches l where p_l exceeds H

$$\Delta p = p_l - H \quad \forall \quad p_l > H \quad (11)$$

Δu_{zp} is the pressure difference Δp times the compliance $C_{kk}^{(zz)}$ of the patch due to a load on itself

$$\Delta u_{zp} = \Delta p C_{kk}^{(zz)} \quad (12)$$

The elastic contact calculation and the plastic surface update are performed iteratively until the following condition is fulfilled

$$p_l \leq H \quad l = 1, \dots, M \quad (13)$$

The surface hardness H is assumed to be three times the yield stress of the sheet material as quantified by Bowden and Tabor [2]. The influence of junction growth due to the combined action of normal and tangential forces could be modelled by employing a modified surface hardness depending on both normal and tangential load. Furthermore the influence of plastic deformation of the sheet on the surface hardness as observed by Wilson and Sheu [6] could be respected in H . Both effects are not considered in the present model.

The real contact area calculated in the normal contact simulation forms the input for the tangential contact simulations. The tangential contact is simulated similar to the normal contact and is described in detail in [7]. The local shear stress τ_{max} is limited to the shear limit τ_o by a local Tresca condition in the real contact area.

$$\tau_{max} = \tau_o \quad (14)$$

EXPERIMENTAL SETUP

As previously described, the ability to model numerically the different contact situations and thus the tribological conditions in sheet-bulk metal forming is important for the general investigation of this new class of forming processes. To ensure the reliability of the developed simulation model the validation of the different stages of development is essential for this purpose. For the validation of the first stage of the simulation model a test rig for the in situ investigation of flattening of sheet metal topographies under normal force and the strip drawing test were used. According to Bowden and Tabor [2] the real contact area A_{real} between workpiece and tool is always smaller than the apparent contact area A_o , because of the roughness of workpiece and tool. For the development of a reliable numerical model the consideration of elastic and plastic flattening in accordance to the surface load and the material properties is very important. To validate the numerical model concerning the flattening behaviour of sheet metal surfaces under normal load a test rig with an ultrasonic measurement setup for in situ monitoring of A_{real}/A_o was used. Main component of the ultrasonic setup is a transceiver probe that is used for the measurement of changes of A_{real} [8, 9]. The ultrasonic waves are emitted by the probe and propagate through the coupling medium water into the steel punch and reach the contact of punch and workpiece. The propagation of ultrasonic waves is depending on the difference in densities of the materials that are passed through. In case of no contact between punch and workpiece, there is transition from steel to air and thus a high difference in density, leading to reflection. When there is contact between punch and workpiece the ultrasonic waves are transmitted, because of the low density difference of the steel-steel pairing. By comparing emitted and reflected ultrasonic intensity, the increase of A_{real} can be quantified. A sketch of the setup and the measurement principle is shown in figure 2. To be able to correlate A_{real} with measurement signal calibration measurements were done. Additional information to the setup and its calibration can be found in [10]. For the tests zinc coated DC04 sheet metal with an electro discharge texture (EDT) was used. The sheet was cleaned with acetone (Dimethylketon) in an ultrasonic bath, to remove all anticorrosive oil from the surface, as the numerical model in the first stage of development is not able to consider the effects of lubricants. For the tests the surface load was increased stepwise from 10 MPa, which is the lowest adjustable surface load, up to 380 MPa. The result of the measurement is shown in the following section, where it is compared to the simulated flattening of the topography. To be able to simulate the flattening under normal load, the surface of the specimen was measured with a confocal white light microscopy in initial state. The data was used as input for the simulation.

As the strip drawing test is well established for determination of friction coefficients in sheet metal forming [11], it was used to validate the simulation model concerning a virtual strip drawing test. In our case a two sided strip drawing test is used, thus for the determination of the friction coefficient μ the drawing force F_F has to be divided by twice the normal force F_N .

The dies are made from tool steel 1.3343, hardened to 62 ± 2 HR, and lapped to an arithmetic mean roughness value of $S_a = 0.22 \mu\text{m}$. As specimen uncoated EDT-structured DC04 strips with a length of 500 mm, a width of 300 mm and a sheet thickness of 2 mm are used. The dies have a length of 100 mm and a width of 55 mm. According to the boundary condition of the simulation model the strip drawing tests were run without lubrication. Because of the dry friction conditions and thus the risk of galling, low normal loads of 3 and 5 MPa were chosen while having a drawing speed of 100 mm/s. The surface was measured in the initial state with a confocal white light microscopy and used as input data for the simulation. The results of the strip drawing test compared to the simulation are shown in the following chapter.

FIGURE 2. Ultrasonic measurement setup (a) and measurement principle (b)

RESULTS

Normal contact

The measured area-pressure curve shows a nonlinear behaviour for large pressures which is in agreement with the findings of Pullen and Williamson [3]. They predict higher contact pressures than the surface hardness H due to hydrostatic stress states underneath the surface. With higher A_{real} the interaction between the roughness asperities is rising, which promotes the development of hydrostatic stress states and consequently higher contact pressures.

In the numerical simulation the Young's modulus E of the DC04 sheet was set to 205 000 MPa and the Poisson's ratio ν was set to 0.34. According to the experimental findings of Bowden and Tabor the surface hardness H was set to three times the yield stress σ_y of the material. For the case of the DC04 sheet with a yield stress of 200 MPa this leads to a surface hardness of 600 MPa. The shear limit τ_o was set to 100 MPa according to the Tresca yield criterion. The simulations for elastic and plastic contact were performed with 256 times 256 surface points and show a linear pressure-area relationship. For the elastic calculation this confirms the results of Archard [1]. However, due to the extremely high local contact pressures, the elastic calculation can only be seen as a lower limit for A_{real} . For the plastic calculation, about 95% of A_{real} is plastic contact area, so that the halfspace model predicts an A_{real} only slightly higher than the analytical model of Bowden and Tabor [2] (see eqn. 1). The model of Bowden and Tabor does not consider elastic contact areas where the pressure is below H so that it always predicts a lower A_{real} than the plastic halfspace model. The halfspace model does not take into account contact pressures above H as observed by Pullen and Williamson, which would increase the real contact area. The influence of the elastic contact area should be small because this area is small. Consequently the plastic contact simulation should give an upper approximation of A_{real} . The soft zinc coat of the DC04 sheet can not be taken into account in the numerical model, so that the calculated real contact area is lower than the measured A_{real} even for the plastic calculation.

Surfaces get flattened in initial contact by plastic deformation. When surfaces are reloaded afterwards the contact is mostly elastic and A_{real} is significantly higher than in first contact. This is an important effect in sheet-bulk metal forming, where the sheet surface can be drawn from zones of high contact pressure to zones of lower contact pressure. The reloading simulations in figure 3b show this effect.

FIGURE 3. Pressure-area relationship (a) and pressure-area relationship in detail (b)

Tangential contact

Figure 4 compares friction coefficients measured in strip drawing tests with numerical results. The strip drawing tests were performed without lubrication and the numerical simulation was done with the plastic model. For both normal pressures the numerical and the experimental value of the friction coefficient are in good agreement. The numerical values are only slightly higher than the experimental values. The value of the maximum shear stress (τ_o) in the real contact area can be considered as an upper bound of the real shear limit of the interface. This leads to the conclusion that the real contact area calculated in the plastic simulation is a quite good approximation of the reality.

FIGURE 4. Friction coefficients in strip drawing tests and numerics

CONCLUSION

The good agreement between the strip drawing tests and the numerical simulations show that the presented halfspace model is an adequate technique to simulate the contact of rough surfaces. The actual behaviour of roughness peaks depends on the three-dimensional stress state underneath the surface. Therefore it is necessary to improve the modelling of plastic deformation within the halfspace simulations. This is currently done by implementing three-dimensional plastic deformation using the von Mises yield criterion. Moreover the retarding effect of hydrostatic pressure in closed lubricant pockets on asperity flattening is presently integrated into the halfspace model. Further measurements with the existing and with other experimental setups are necessary to gain more knowledge of the interaction of rough surfaces and to validate the simulation model.

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