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Multi-scale friction modeling for sheet metal forming: The boundary lubrication regime

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ABSTRACT

A physical based friction model is presented to describe friction in full-scale forming simulations. The advanced friction model accounts for the change in surface topography and the evolution of friction in the boundary lubrication regime. The implementation of the friction model in FE software codes is discussed. Results show that friction coefficients vary in space and time, and depend on local process conditions such as the nominal contact pressure and the plastic strain in the sheet material. The advanced friction model is validated by two small-scale forming processes, proving the enhanced predictive capabilities of FE simulations. The moderate increase in FE computation time, compared to using a Coulomb based friction model, demonstrates the efficiency of the proposed friction model.

1. Introduction

Significant improvements have been made in the numerical simulation of metal forming processes in the last decade. An accurate forming analysis can however only be made if, amongst others, the friction conditions between the sheet material and the tools are described accurately. In the majority of FE simulations 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 the type of lubricant used. Hence, a physical-based friction model which accounts for a varying friction coefficient will enhance the accuracy of numerical forming simulations [1–4].

Boundary lubrication is a common lubrication regime in sheet metal forming. In this regime, a normal contact load is solely carried by contacting surface asperities. The real area of contact, playing an important role in characterizing friction, relies on the roughness characteristics of both the tool and the workpiece surface. The workpiece surface is liable to changes due to flattening and roughening mechanisms, changing the real contact area.

The main flattening mechanisms during sheet metal forming, which tend to increase the real area of contact, are flattening due to normal loading, flattening due to sliding and flattening due to combined normal loading and deformation of the underlying bulk material. Roughening of asperities, observed during deformation of the bulk material without applying a normal load to the surface, tends to decrease the real area of contact [5,6]. Most of the theoretical models describing the flattening behavior of asperities continue the pioneering work of Greenwood and Williamson [7], who proposed an elastic contact model that accounts for a stochastic description of rough surfaces. Over recent years, modifications have been made to this model to account for arbitrarily shaped asperities [8], plastically deforming asperities [9,10], the interaction between asperities [8,11] and the influence of stretching the underlying bulk material [12,13]. Another technique to describe the flattening behavior of asperities relies on variational principles, first introduced by Tian and Bhushan [14]. Variational principles account for the fractal behavior of rough surfaces and include the long-range elastic coupling between contacting asperities. Elastic perfectly plastic contact conditions, including the unloading behavior of asperities, can be described using this approach. Besides the analytically based models described above, techniques can be used that account for a deterministic description of rough surfaces. In conjunction with, for example, FE techniques, realistic 3D surfaces can be examined under different loading and bulk straining conditions. Korzekwa et al. [15] were one of the first who adopted a plane strain FE approach to derive empirical relations for the description of asperity flattening under combined normal loading and straining of the bulk material. Although the FE approach has proven its applicability in many engineering applications, simplifying assumptions have to be made to ensure reasonable computation times with respect to modeling 3D rough surface textures.

Compared to normal loading only, a further increase in real contact area can be caused by sliding. The increase in real contact area reduces the mean pressure at contact spots, accommodating the additional shear stresses. The increase in real contact area is

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referred to as junction growth [16], and is a known phenomenon for dry contacts [17–20]. In this case, the required shear stress to initiate junction growth is introduced by the adhesion effect between dissimilar materials. For lubricated contacts, a similar effect such as junction growth has been observed by Emmens [21] and Lo and Tsai [22].

Friction is caused by ploughing and adhesion between contacting surface asperities. Wilson [23] and Challen and Oxley [24,25] developed models to account for these effects. Wilson [23] treated the effect of adhesion and ploughing on friction separately, while Challen and Oxley took the combined effect of ploughing and adhesion into account. Challen and Oxley deduced slip-line fields to describe friction between one wedge-shaped asperity and a flat soft workpiece surface. Friction between multiple tool asperities and a flat soft counter surface can be obtained by describing the tool surface in terms of stochastic parameters [8]. To establish the translation from single asperity scale to multiple asperity scale, the summit height distribution of the tool, the asperity density and the mean radius of tool asperities are required. However, such ploughing models tend to lose their applicability under high fractional real contact areas. In these areas, tool asperities form contact patches which penetrate into the softer workpiece material [26,27]. The frictional behavior of the contacting surfaces now depends on the geometry of the contact patches, rather than the geometry of the individual asperities. In addition, the required stochastic parameters are known to be dependent on the resolution of the measured surface texture [28]. Ma et al. [29] proposed a multi-scale friction model that accounts for asperities forming contact patches under high fractional real contact areas. A deterministic surface description is used in their approach, which excludes the use of a summit height distribution, the asperity density and the mean asperity radius, and therefore excludes possible scale dependency problems.

A boundary lubrication friction model is presented in this paper. A friction framework has been developed that comprises existing, adapted and newly developed models. Because micro-mechanical friction models are generally regarded as too cumbersome to be used in large-scale FE simulations, the choice of the implemented models is a trade-off between accuracy and computational efficiency. This will yield a physically based friction model that is still computationally attractive for use in large-scale forming simulations. The framework distinguishes 3 stages. In the first stage, the input step, surface characteristics and material properties are defined. A method to measure 3D surfaces and an experimental procedure to obtain model parameters is discussed. Stage 2, the asperity deformation step, includes models to describe surface changes due to normal loading, deformation of the underlying bulk material and sliding, see Section 2. The models are based on a stochastic description of a rough workpiece surface in contact with a flat tool surface, and provide an expression for the fractional real area of contact. A non-linear work-hardening normal loading model is presented which is based on energy and volume conservation laws. Asperity flattening due to combined normal loading and deformation of the underlying bulk material has been described by the flattening model proposed by Westeneng [8]. The increase in real contact area due to sliding is captured by adopting the junction growth theory as proposed by Tabor [16]. The final stage, the friction evaluation step, accounts for the influence of ploughing and adhesion on friction. The contact model of Ma et al. [29], which was originally developed to describe friction in extrusion processes, has been adapted to model friction in metal forming processes, see Section 3. In contrast to the asperity deformation models, this model accounts for a deterministic description of the rough workpiece and tool surface, in which the calculated deformation of workpiece asperities in stage 2 is used to adapt the surface texture of the workpiece. The plateaus of the flattened workpiece asperities are assumed to be perfectly flat, in which the harder tool asperities are penetrating. The summation of shear forces acting on individual contact patches (collection of penetrating tool asperities) is used to finally obtain the friction coefficient. The final section describes the implementation of the boundary lubrication friction model in an FE software code. Two deep drawing applications will be discussed to demonstrate the applicability of the advanced friction model to large-scale forming simulations.

2. Modeling the deformation behavior of rough surfaces

The models implemented within the asperity deformation step are discussed in this section. First, the normal loading model is discussed in Section 2.1. The influence of sliding on the real contact area is outlined in Section 2.2. Finally, a model for combined normal loading and deformation of the underlying bulk material is discussed in Section 2.3.

2.1. Flattening due to normal loading

In most of the contact models the asperity density, the mean asperity radius and the *summit* height distribution are used to calculate the amount of asperity deformation, which was first introduced by Greenwood and Williamson [7]. Summit based stochastic parameters depend on the resolution of the scanning method used. Westeneng [8] proposed an ideal-plastic contact model that accounts for the *surface* height distribution instead of the *summit* height distribution to describe rough surfaces. The *surface* height distribution is based on measured surface points, which excludes the use of summit based stochastic parameters. The contact model proposed in this section is based on the normal loading model described by Westeneng. The newly developed contact model accounts for work hardening in deforming asperities. Moreover, compared to the contact model of Westeneng, the shear stress between crushing and raising asperities is accounted for.

A rigid and perfectly flat tool is assumed contacting a soft and rough workpiece material. This is considered a valid assumption as the tool surface is in general much harder and smoother than the workpiece surface. The roughness texture of the workpiece is modeled by bars, which can represent arbitrarily shaped asperities, see Fig. 1. The cross sectional area of these bars is taken to be equal to the resolution of the measured (or digitally generated) 3D surface texture. Three stochastic variables are introduced to make the translation from micro-scale to macro-scale modeling of contact: the normalized surface height distribution function of the rough workpiece surface $\phi_{\mathrm{w}}(z)$, the uniform raise of the non-contacting surface U_{L} (based on volume conservation) and the separation between the tool surface and the mean plane of the rough workpiece surface d_{L}. The suffix L in d_{L} and U_{L} refers to the normal loading step.

The crushing and raising behavior of deformed bars relies on a proper description of the material behavior. In this paper, it is assumed that the maximum pressure a bar can carry equals the hardness H of the material. By approximation, the hardness H is given by

$$H = B\sigma_{\mathrm{y}} \tag{1}$$

with $B \approx 2.8$ for steel materials [16]. The physically based isothermal Bergström van Liempt [30–33] hardening relation is used to describe the yield strength σ_{y}.

The total plastic strain ε in the bars is related to the reference height λ. The reference height reflects an empirical length scale to be determined from experiments (see Section 4). The reference height is taken to be equal for all bars, see Fig. 1. By using λ,