Wear 286–287 (2012) 66–78

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Advanced friction modeling for sheet metal forming

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ARTICLE INFO

Article history:
Received 15 November 2010
Received in revised form 22 February 2011
Accepted 8 April 2011
Available online 20 April 2011

Keywords:
Friction modeling
Friction mechanisms
Asperity contact
Flattening
Real contact area
Ploughing

ABSTRACT

The Coulomb friction model is frequently used for sheet metal forming simulations. This model incorporates a constant coefficient of friction and does not take the influence of important parameters such as contact pressure or deformation of the sheet material into account. This article presents a more advanced friction model for large-scale forming simulations based on the surface changes on the micro-scale. When two surfaces are in contact, the surface texture of a material changes due to the combination of normal loading and stretching. Consequently, shear stresses between contacting surfaces, caused by the adhesion and ploughing effect between contacting asperities, will change when the surface texture changes. A friction model 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. This friction model has been implemented in a finite element code and applied to a full-scale sheet metal forming simulation. Results showed a realistic distribution of the coefficient of friction depending on the local process conditions.

1. Introduction

The automotive industry makes extensive use of 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. However, an accurate forming analysis of an automotive part can only be made if, among others, the material behavior and friction conditions are modeled accurately. For material models, significant improvements have been made over recent decades. However, in the majority of simulations a simple Coulomb friction model is still used. This model does not incorporate the influence of important parameters on the contact behavior, 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 and springback 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. At the 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 lubricant flow – as in the mixed lubrication regime – or fully carried by the lubricant – as in the hydrodynamic lubrication regime – hydrodynamic shear stresses will contribute or even predominate. This article will focus on the two friction mechanisms present in the boundary layer regime: ploughing and adhesion.

Wilson [1] developed a model which treated the effect of adhesion and ploughing separately. A more advanced model was developed by Challen and Oxley [2] which takes the combined effect of ploughing and adhesion on the coefficient of friction into account. Challen and Oxley performed a slip-line analysis on the deformation of a soft flat material by a hard wedge-shaped asperity and derived expressions for the coefficient of friction and wear rates. Westeneng [5] extended the model of Challen and Oxley to describe friction conditions between multiple tool asperities and a flat workpiece material. Their 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 amount of ploughing and adhesion depends on the real area of contact. Hence, the coefficient of friction will change if the real area of contact changes. The real area of contact depends on the various flattening and roughening mechanisms of the deforming asperities. The three dominating flattening mechanisms during SMF processes are: (1) flattening due to normal loading [6]; (2) flattening due to stretching [7,8]; and (3) flattening due to sliding [9]. Flattening increases the real area of contact, resulting in a higher

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doi:10.1016/j.wear.2011.04.004

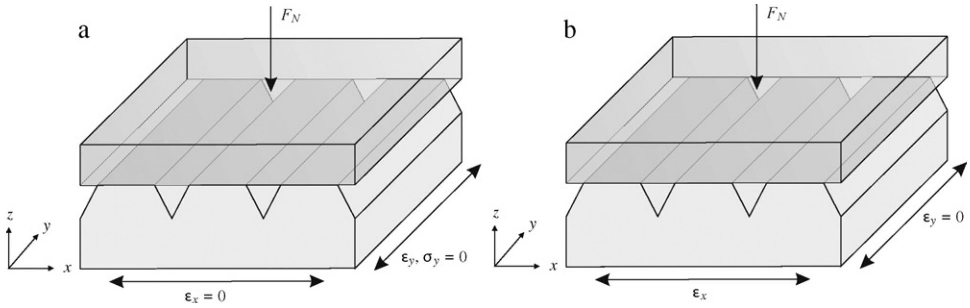

Fig. 1. Representation plane-stress model of Wilson and Sheu (a) and plane-strain model of Sutcliffe (b).

coefficient of friction. Roughening of asperities, observed during stretching of 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 article are flattening due to normal loading and flattening due to stretching. Future work is planned on modeling the roughening effect and the influence of sliding on the flattening behavior.

A major 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 and Williamson [6] which developed a stochastic model based on contact between a flat tool and rough workpiece surface. Their model mathematically describes contact between two surfaces based on the assumption that summits of the rough surface are spherical, that summits only deform elastically and that the surface texture can be described by a distribution function. Over recent decades, modifications have been made to this model to account for arbitrary shaped asperities, plastically deforming asperities and the interaction between asperities. Zhao and Chang [11] developed a model to describe interactions between asperities on the micro-scale using the Saint-Venant principle and Love's formula (elastic interaction between asperities is assumed). This model is integrated into the elastic-plastic contact model of Zhao, Maietaa and Chang (ZMC-model) [12] which includes a transition regime from elastic to fully plastic deformation of asperities. Jeng and Wang [13] extended the ZMC-model for elliptical contact situations and Pugliese et al. [14] for parabolic profile approximations. Pullen and Williamson [15] developed an ideal plastic contact model based on the conservation of volume during plastic deformation and the assumption that displaced material reappears as a uniform rise in the non-contacting surface. Conservation of energy is used to obtain relations between the contact pressure, separation and real area of contact as a function of the surface height distribution. The model of Pullen and Williamson inspired Westeneng [5] to derive an ideal-plastic and nonlinear-plastic contact model based on the conservation of volume and energy. Westeneng modeled the asperities as 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]. Wilson and Sheu [7] developed an analytical upperbound model to describe the flattening behavior using wedge-shaped asperities with a constant angle, Fig. 1(a). The length of the asperities is much greater than the width of the asperities. Therefore, a plane-strain state transverse to the asperities (x-direction) and a plane-stress state in the direction of the asperities (y-direction) is assumed since the stress in this direction might be neglected. The semi-empirical relation of Wilson and Sheu provides a relation between the effective hardness, the real area of contact and a non-dimensional strain rate. Sutcliffe [8] extended the model of Wilson and Sheu to describe a plane-strain situation in the direction of the asperities (strain in y-direction equals zero, Fig. 1(b)). A slip-line analysis is performed to describe the flattening of transverse wedge-shaped asperities. Westeneng [5] developed a strain model which describes the influence of strain on a surface geometry using arbitrary shaped asperities. His method is based on volume and energy conservation laws and assumes that the crushed asperities cause a constant rise of the non-contacting asperities. The model is applicable to both plane-strain and plane-stress situations, depending on the definition of the non-dimensional strain rate [5].

The objective of this article is to present a friction model that couples the most important friction mechanisms and to show the applicability of a micro-based friction model in large-scale forming simulations. The emphasis of this article is focused on the development of a numerical framework and the implementation of this framework in FE codes. For this purpose, existing models have been used to describe the various friction mechanisms:

- To describe the flattening behavior of asperities due to normal loading the contact model of Westeneng [5] has been used. His contact model include flattening parameters which are not included in other loading models. Therefore, the model of Westeneng will likely have better predicting capabilities in describing the flattening behavior of asperities than other models.
- The flattening behavior of asperities due to straining has been described by the strain model of Westeneng [5]. The strain model of Westeneng includes flattening parameters which are not accounted for in other models. Especially the possibility to describe arbitrarily shaped asperities makes the strain model preferable to others.
- The influence of ploughing and adhesion on the coefficient of friction has been described by the extended model of Challen and Oxley [2,5]. The ability to describe contact problems between multiple asperities makes this extended version favorable.

An overview of the friction model is presented in this article and the translation from micro to macro modeling is outlined. The theoretical background of the models used to describe the various friction mechanisms is described and the implementation in FE codes is discussed. The flattening models are validated by means of FE simulations on the micro-scale and the applicability of the friction model in FE codes is proven by a full-scale sheet metal forming simulation.

2. Theoretical background

2.1. Unified friction theory

A friction model, to be used in finite element codes, has been developed to couple the various micro friction models, Fig. 2.