Evaluation of surface asperity based contact friction models under different conditions

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Abstract. Finite element (FE) simulation has been often used to optimize sheet metal forming process. In order to increase predictive capability for the formability and springback of sheet metals in the FE simulations, advanced numerical techniques and constitutive models have been regarded as critical issues and thus investigated by numerous researchers. However, most of the sheet metal forming simulations employed the Coulomb friction law with a constant value, which in fact is known to be a function of contract pressure, surface quality and sliding velocity. In this study, the asperity based friction model proposed by Westeneng [1], as one of most promising microscale models, was investigated and evaluated by introducing different contact assumptions. Modified friction model was evaluated for estimating the friction coefficient under different variables influencing the frictional condition.

1. Introduction
Numerical simulations such as finite element analyses have been frequently applied to the product or process optimization in the sheet metal forming industries. To increase the accuracy of the FE simulations, advanced numerical techniques and constitutive models have been proposed and implemented by numerous researchers. However, the friction between the sheet metal and tool in most of simulations has been modeled by the simple Coulomb friction law. However, it is well known that the friction behavior is very complicated and depends on many factors such as contact pressure, surface quality, lubricant properties, process condition and environment [2,3]. Therefore, a reasonable description of frictional behavior is required for the accurate modeling of sheet metal forming. In order to model the friction laws for the sheet metal forming simulations, there have been various approaches which can be classified as either phenomenological or micromechanical models. In the phenomenological model, a mathematical equation is derived based on experimental observations in friction tests under different contact conditions. For example, Lee et al. [4] measured the friction coefficients for different contact pressures and sliding velocities, and proposed an equation of friction coefficient as a function of contact pressure and punching velocity. Though this approach describes the real friction coefficient measured by experiments, it requires a large number of tests for limited contact conditions. In the micromechanical approach, fundamental mechanisms of interactions between contact surfaces are considered in micro-scale. A ploughing effect, the local plastic deformation of asperities, is...
the major mechanism in high contact pressure on microscopic level [5]. These mechanisms are embodied into the micromechanical model to derive the restraining force and friction coefficient [1].

In general, three lubrication regimes can be distinguished to describe lubricant flow between the contact surfaces during the metal forming process. This study focuses on the boundary lubrication in which the critical contact regions, such as tool corners, dominates in the forming operation. The current model is based on the understanding of the friction mechanism at micro-scale and the asperity deformation model proposed by Westeneng [1] to predict the friction coefficients. In particular, underlying assumptions for the analytical solutions were investigated and the calculated friction coefficient was applied to the simulation of sheet metal forming.

2. Friction model proposed by Westeneng [1]

In this study, the friction model by Westeneng was used as a reference model because it has been considered as one of most promising friction models at microscale. The main mechanisms of the reference model consist of flattening and ploughing. In the flattening model, the workpiece is assumed to be rougher and softer than tools in sheet metal forming. Thus, the tool is assumed as rigid and perfectly flat. The asperities of the rough workpiece are modeled by group of bars with different heights, which represent surface height distribution function as in Figure 1. As contact occurs due to normal pressure, asperities are indented under the assumption that the energy and volume conservation laws are satisfied. Then, the real contact area between the workpiece and tool is calculated as in Figure 2(a).

As previously mentioned, ploughing effect is dominant during friction in sheet metal forming processes. According to the combined effect of ploughing and adhesion between a round-shaped asperity and a flat surface, the model by Challen and Oxley [8,9] proposed the friction coefficient equation of the single asperity. Westeneng [1] adopted the models of Challen and Oxley to describe friction conditions between a flat workpiece and multiple tool asperities:

\[
F_w = \rho_\alpha A_{nom} \int_{\delta}^{s_{max}} f_{asp}(\omega) \phi(s) \, ds
\]

where \(\omega\) is the length of indentation, \(\alpha\) is the ratio of the actual contact area of the workpiece and the nominal contact area, \(\rho_\alpha\) the asperity density of the tool summits, \(A_{nom}\) the nominal contact area, \(\phi\) is the normalized surface height distribution function of the tool summits, \(f_{asp}\) the friction force at single asperity scale [9], and \(F_w\) the total friction force. The bounds of the integral are described by \(s_{max}\), the maximum height of tool summit, and \(\delta\) the separation between the mean plane of the tool summits and the flat workpiece surface. The friction coefficient can be derived by the following equation.

\[
\mu = \frac{F_w}{F_N} = \frac{\rho_\alpha A_{nom} \int_{\delta}^{s_{max}} f_{asp}(\omega) \phi(s) \, ds}{p_{nom}A_{nom}} = \rho_\alpha \int_{\delta}^{s_{max}} f_{asp}(\omega) \phi(s) \, ds \frac{\alpha}{p_{nom}}
\]
where $F_N$ the normal contact force, and $p_{nom}$ the nominal contact pressure. For details on the friction model proposed by Westeneng, refer to [1,6].

As $\delta$ represents the magnitude of indentation of the tool summit asperities, this value is a dominant factor to determine friction coefficient in this model. Since the whole tool summits are assumed to be in contact with the workpiece surface in the Westeneng model [1], $\delta$ is determined as

$$\delta = s_{\min}$$ (3)

Therefore, the variable for $p_{nom}$ the nominal contact pressure, in equation (2) is only $\alpha$, the fraction of the real contact area, which significantly influences the friction coefficient equation (2). From Equation (2), it is seen that the ratio $\alpha / p_{nom}$ influences the friction coefficient, which leads to decrease in friction coefficient as the contract pressure increases as shown in Figure 2(b).

![Figure 2](image)

**Figure 2.** (a) The fraction of real contact area as a function of contact pressure and (b) the friction coefficient as a function of the contact pressure under friction model proposed by Westeneng [1].

### 3. Modified friction model

In numerous literatures, the friction coefficient showed decreased tendency with increasing contact pressure. However, other reversed trends are also reported as in [4]. For example, Lee et al. [4] reported that the friction coefficient increases with increasing contact pressure up to 50 MPa, then it decreases and saturates at higher contact pressure. The friction coefficient always decreases as the contact pressure increases in the referenced model [1]. In the new model, $\delta$ is iteratively calculated until the following equation (4) is satisfied. Specifically, $\delta$ increases from $s_{\min}$ to the converged solution of equation (4).

$$F_N = p_{nom}A_{nom} = \rho_\tau \alpha A_{nom} \int_\delta^{s_{\max}} A_{asp} (\omega) H \phi (s) ds = \rho_\tau \alpha A_{nom} \int_\delta^{s_{\max}} F_{Nasp} (\omega) \phi (s) ds$$ (4)

where $A_{asp}$ is the area of each tool summit, $F_{Nasp}$, the normal force of each tool summit, and $H$ the hardness of the workpiece. Equation (4) is based on the force equilibrium, in which the total indented force ($A_{asp}H$) by each tool summit asperity is the same as external force, $p_{nom}A_{nom}$ as illustrated in Figure 3. Therefore, $\delta$ is a function of the contact pressure, $p_{nom}$ as in Figure 4(a). Unlike the Westeneng model, in which the friction coefficient is determined by the ratio of $\alpha$ to the contact pressure, the relationship between $\alpha$ and $\delta$ determines the friction coefficient in the modified model. Consequentially, as the surface condition is changed, the friction coefficient can be described more flexibly; i.e., for both cases with increasing or decreasing friction coefficient as a function of contact pressure as shown in Figure 4(b). Note that the two conditions (condition 1 and condition 2) were chosen as numerical sensitivity study for an illustrative purpose and their material and surface properties are listed in Table 1.
Figure 3. Indentation tool summits and schematically shown force equilibrium between the external force and total indented force by each tool summit asperity

Figure 4. (a) The separation between the mean plane of the tool summits and the workpiece surface as a function of contact pressure and (b) the friction coefficient as a function of the nominal pressure

4. Conclusions

In this study, the existing asperity based friction model at micro-scale was first analysed. To extend the model’s flexibility to accommodate the increasing or decreasing trends of friction coefficients in experiments, a modified friction model by applying force equilibrium was proposed. Considering different material properties and surface conditions, the friction coefficient could be flexibly described in the modified friction model. The calculated friction coefficient as a function of contact pressure will be implemented continuum level finite element simulation for sheet metal forming.

Table 1. Surface and material properties of workpiece and tool in conditions 1 and 2 in Fig. 4(b)

| Workpiece property | Tool property |
|--------------------|--------------|
|                    |              |
| Hardness [MPa]     | Standard deviation of surface height distribution [μm] | Standard deviation of surface height distribution [μm] | Asperity density of tool summits [1/μm²] |
| Condition 1        | 700          | 1.5         | 0.15          | 0.019          |
| Condition 2        | 1400         | 1.25        | 0.175         | 0.022          |

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