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A friction model for loading and reloading effects in deep drawing processes ☆

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ABSTRACT

Deep drawing is one of the most widely-used forming processes to manufacture automotive body parts from sheet metal. In order to simulate deep drawing processes, a finite element (FE) method was used to predict formability. The accuracy of the FE simulation depends on the material models, numerical techniques, and contact algorithms. Despite the fact that the contact conditions between the tool and sheet material influences the coefficient of friction in forming processes, the coefficient of friction is often treated as a constant Coulomb friction coefficient in FE simulations. However, a friction model based on local contact conditions and surface topography is required to improve forming predictability. There is growing interest in developing contact models to predict the nature of friction conditions for use in FE calculations. In deep drawing processes, the sliding contact predominantly occurs in the blank holder region between the tool and sheet material. The contact pressure in the blank holder is non-uniform due to bending and material compression which vary depending on tool geometry. The sheet metal surface is subjected to repeated contact during sliding, which in turn affects the local friction conditions. The objective of this paper is to develop a sliding friction model for mixed modes of surface deformation. The deterministic approach used in the current model includes the roughness of both the sheet material and the tool. The sheet material is subject to an asperity flattening process. Further, the tool surface indents into the sheet material under normal loading. The geometry of the asperities is characterized by an elliptical paraboloid shape to better calculate the load-dependence of friction. The model has been compared with data from experiments using a rotational friction tester under multiple loading conditions.

1. Introduction

1.1. *Contact conditions in deep drawing processes*

Deep drawing process involves the forming of the sheet metal to the required shape using a die and punch. Complex contact conditions occur between the sheet metal and tool when sliding over the die rounding region due to the combined bending and tensile forces [1] as shown in Fig. 1. The contact pressure is not uniform in the blank holder and die rounding regions and the sheet metal surface is subjected to repeated contacts under varying loads. For example, when the sheet material slides over the die rounding region (marked as 1–3 in Fig. 1) the surface is locally loaded to a high contact pressure followed by lower contact pressures. At the micro-scale, the contact occurring between the surfaces is discrete. The surface topography is composed of micro irregularities, called as asperities. The formation of junctions at the micro-contacts due the application of load governs the friction as proposed by Tabor [2]. The junction theory has been further used to develop contact models to describe surface deformation process. Statistical methods have been developed by Greenwood and Williamson [3] and Pullen and Williamson [4] to describe the surface deformation process. For metal forming processes, the surface deformation is complex and the contact models have been extended to describe the bulk deformation process by Wilson and Sheu [5] and Sutcliffe [6] using a wedge shaped asperity for plane stress and strain conditions. Various experimental techniques have also been developed to measure the coefficient of friction by simulating the conditions occurring in deep drawing processes. The choice of experiment depends on how the deformation behaviour is controlled. For a simple deep drawing process (for example cup drawing test or U-shaped strip drawing test) as a test method, punch forces can be measured to quantify the effect of surface roughness and lubrication effects.

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Nomenclature

a	semi-major radius of elliptical paraboloid asperity [m]
b	semi-minor radius of elliptical paraboloid asperity [m]
f_d	boundary layer degradation factor [dimensionless]
f_{hk}	interfacial friction factor [dimensionless]
h	surface separation [m]
k	shear strength of deforming material [Pa]
m	elliptic integral parameter [dimensionless]
A	contact area of an asperity [m^2]
C_A	critical contact area at the onset of plasticity [dimensionless]
E	elliptic integral of the second kind for the elliptical paraboloid asperity [dimensionless]
E^*	combined elastic modulus of the contacting materials [Pa]
F	force [N]
H	hardness of the deforming material [Pa]
K	elliptic integral of the first kind for the elliptical paraboloid asperity [dimensionless]
K_υ	contact pressure factor for the hardness of deforming material [dimensionless]
P_m	mean Hertzian contact pressure [Pa]
P_{nom}	nominal contact pressure [Pa]
R	radius of the elliptical paraboloid asperity [m]
S_q	root mean square of the surface roughness [m]
α	non dimensional semi-axis of contact ellipse in major direction [dimensionless]
β	non dimensional semi-axis of contact ellipse in minor direction [dimensionless]
γ	non dimensional interference of elliptical paraboloid [dimensionless]
δ	non dimensional interference of asperity, [dimensionless]
κ	ellipticity ratio of asperity [dimensionless]
λ	asperity curvature ratio [dimensionless]
μ	coefficient of friction [dimensionless]
υ	Poisson ratio [dimensionless]
φ	orientation of the elliptical paraboloid asperity with sliding direction [°]
σ_y	yield strength of the deforming material [Pa]
σ_κ	standard deviation of the asperity curvature [m^{-1}]
σ_s	standard deviation of the asperity slope [m^{-1}]
τ_{BL}	shear strength of boundary layer [Pa]
ψ	bandwidth parameter of surface [dimensionless]
ω	interference of asperity [m]

Subscript

1	transition point for interference from elastic to elastic–plastic deformation mode
2	transition point for interference from elastic–plastic to full plastic deformation mode
e	elastic deformation mode
ep	elastic–plastic deformation mode
p	fully plastic deformation mode
t	tool
wp	workpiece (sheet material)
x	major direction of elliptical paraboloid asperity
y	minor direction of elliptical paraboloid asperity
W	frictional force
N	normal force

Superscript

$'$	tool asperity
ul	unloading mode
$trans$	transition load/area at the onset of plasticity

However, the individual effects like normal loading, stretching and repeated contacts for surface deformation cannot be quantified. Strip drawing test has been used by ter Haar [7] to measure the effect of surface deformation (due to normal loading and pre-stretching) and sliding speed to construct a Stribeck curve for deep drawing process. The friction is found to be hardly influenced by the bulk deformation process. Roizard et al., [8] has also used a strip drawing test to measure the friction for sheet metal forming to study the influence of repeated contacts and temperature influence. They showed that the coefficient of friction in repeated contacts has increased due to adhesive transfer of material. Emmens [9] used a rotational friction tester to study the influence of surface roughness, lubrication and various material combinations only for normal loading conditions. Jonasson et al., [10] used a bending under tension test to measure the friction using different textured surfaces by replicating the deformation zone in die radius. Wiklund et al., [11] also used a bending under tension test to validate a friction model with normal loading, bulk deformation and lubrication effects for different surface textured sheet material at various sliding speed. There has been a wide variety of contact models have been developed as well as experiments have been conducted to understand the tribological behaviour in deep drawing process. The correlation between models and experiments is still lacking to understand the individual effects. This article focuses on improving the predictability of the developed friction models related to normal loading and reloading of surfaces. Bulk deformation adds complexity to the friction measurements in both the strip drawing test as well as bending under tension tests due to change in surface roughness and bending forces respectively. The contact models to predict the coefficient of friction described in [12–21] discusses the effects of asperity flattening due to normal loading and bulk deformation, ploughing, third body effects, boundary and mixed lubrication conditions. However, the deformation of the sheet surface is assumed to be rigid plastic. The current work focuses on improving the contact models for mixed modes of deformation for loading and reloading contact conditions.

1.2. Contact model

Tool and sheet material surfaces are nominally flat. When two nominally flat surfaces are brought into contact, the contact occurs only at certain spots as shown in Fig. 2. Hence, the real contact area is generally smaller than the nominal contact area. The contacting surfaces differ in roughness levels. The tool surface is generally smoother than the sheet material surface. In the contact model, it can be assumed that the tool is smooth at the workpiece (sheet material) roughness scale [12]. The smooth tool flattens the encountered workpiece asperities. The asperities undergo mixed modes of deformation when subjected to loading/reloading of surfaces. An elastic–plastic contact model from Jamari and Schipper [22] is used to describe the deformation of workpiece asperities for reloading contact conditions. At a smaller scale (i.e., tool roughness level), the tool asperities indent into the flattened workpiece. During sliding, the indented tool asperities plough through the workpiece. A tool indentation model for