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Investigation of the strain distribution with lubrication during the deep drawing process

T.S. Yang

Department of Mechanical and Computer-Aided Engineering, National Formosa University, 64 Wunhau Road, Huwei 632, Taiwan

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ABSTRACT

A lubrication/friction model can be implemented in FEM codes to predict the contact area ratio, friction coefficient and strain distribution in lubricated deep drawing process. In the lubrication analysis, the surface roughness effect on lubrication flow is included by using Wilson and Marsault's average Reynolds equation that is appropriated for mixed lubrication with severe asperity contact. With regard to the asperity contact theory, the well-known flattening effect is considered. Friction is expressed in terms of variables such as lubricant film thickness, sheet roughness, lubricant viscosity, interface pressure, sliding speed, and strain rate. The proposed lubrication/friction model combined with a finite element code of deep drawing process to predict the contact area ratio, friction coefficient and strain distribution. Numerical results showed that the present analysis provides a good agreement with the measured strain distributions.

1. Introduction

Friction and lubrication are of great importance in metal forming processes such as deep drawing, stretch forming, extrusion, and forging. Since the strain distribution in the sheet is influenced by friction, the formability of the sheet metal depends not only on the material property but also on the friction at the tooling/blank interface. Hence the presence of an effective lubricant film between contact surfaces in deep drawing process increases the drawability of sheet, reduces wear of tool, and improves the quality of product.

Wilson [1,2] pointed out that the deformed surface topography affects the formation and transport of lubricant film. Hence the different lubrication regimes may occur in different areas of the interface or at different times. This makes the analysis of the tooling/workpiece interface friction with lubrication in metal forming process extremely complicated. Evidence for the formation of hydrodynamic lubrication film under controlled deep drawing processes conditions were reported by Mastrovich [3]. In spite of these observations regarding the presence of hydrodynamic lubrication regime in deep drawing processes, a very few efforts have been placed to develop a theoretical analysis to model the hydrodynamic lubrication for this process. Mahdavian and Shao [4] developed a theoretical model for hydrodynamic lubrication of deep drawing. This analysis was based on the assumption that the film thickness between the metal sheet and the die surface is linear and is independent of the blank holder squeezing action during the deformation of the sheet metal. Mahdavian and Shao [4] separated the lubricant film into two regimes during deformation phase: the compression zone, which is the flat part of the drawing tool, and the die zone, in which the bending of the blank is started and completed. Both the film thickness and the drawing force ratio predicted by theoretical results were compared with experimental measurements. Yang [5] combined the elastic–plastic finite element code of deep drawing process and the full film lubrication theory. The film thickness and the strain distribution in full film lubrication are predicted. The theoretical results showed excellent agreement with the experiment data.

The theoretical work of Mahdavian and Shao [4] and Yang [5] is based on the assumption that there is no asperity contact at the die/workpiece interface. Such a condition is relatively rare in practice. In order to take the surface roughness effect into consideration, Patir and Cheng [6] proposed an average Reynolds equation for analyzing the lubricant flow. Wilson and Marsault [7] recently developed the average Reynolds equation for Christensen surface with arbitrary Peklenik surface pattern parameter, which is considered to be more appropriate to the mixed lubrication with severe asperity contact. With regard to the asperity contact theory, Wilson and Sheu [8] developed a semi-empirical equation to express the relation between the contact area ratio and the non-dimensional effective hardness.

As a first attempt to combine a finite element code with a lubrication/friction model realistically, Wilson et al. [9] successfully simulated the axisymmetric stretch forming. The change of strain distribution owing to the variation of friction coefficient caused by the tribological variables such as lubricant property and roughness of die and workpiece could be predicted correctly by

E-mail address: tsyang@nfu.edu.tw

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Nomenclature

A	fractional contact area ratio
E	location of the boundary between die and compression zone
$\dot{E}_I$	non-dimensional strain rate
$\dot{F}$	nodal force rate
H_a	effective hardness
H_t	non-dimensional mean film thickness
R_q	RMS composite surface roughness
V	blank holder velocity
f_1, f_2	functions of contact area ratio
f_h, f_v	force components per unit undeformed sheet area in the horizontal and vertical directions
h_B	mean film thickness dictated by the blank holder pressure
h_t	mean film thickness
h_{t1}	mean film thickness at boundary between die and compression zone
k	shear strength of blank
p	interface pressure
p_a	asperity peak pressure
p_b	lubricant pressure
p_{BH}	maximum pressure limited by the blank holder
r	local radius
r_c	radius from the origin to the center of the blank holder
r_0	radius of the rim of blank
r_1	radius from the origin to the boundary between die and compression zone
r_2	die radius
t	time
t_0	thickness of blank
u	velocity of blank surface
ε	bulk strain rate
η	lubricant viscosity
θ	angle between blank and surface of die
ϕ_r	pressure flow factor
ϕ_s	shear flow factor
τ_a	adhesion stress
τ_f	friction stress
τ_h	lubricant friction stress
τ_p	plowing friction stress

the suggested friction model. Hsu and Yang [10] extended the same strategy to simulate the influence of tribological variables on strain path and limiting dome height. The results show excellent agreement with experimental measurements.

In this paper, a developed lubrication/friction model is coupled to the elastic–plastic membrane finite element code of deep drawing process. The process analysis of deep drawing was developed by Mahdavian and Shao [4]. The influence of roughness on lubrication is suggested by Wilson and Marsault's average Reynolds equation. The film thickness and strain distribution for various tribological parameters are predicted and compared with the experiment in the present research.

2. Method of analysis

2.1. Finite element analysis of deep drawing process

The "original" elastic–plastic finite element membrane code of Hsu and Yang [10] is adopted in this paper. The model treats plastic flow by a modified von Mises flow rule which satisfies Hill's rate-insensitive normal anisotropic relations. The strain rates consist of an elastic part and plastic part, given by

$$\{\dot{\varepsilon}\} = \{\dot{\varepsilon}^{(e)}\} + \{\dot{\varepsilon}^{(p)}\} \tag{1}$$

where

$$\left\{\dot{\varepsilon}^{(e)}\right\} = \begin{Bmatrix} \dot{\varepsilon}_1^{(e)} \\ \dot{\varepsilon}_2^{(e)} \end{Bmatrix} = \frac{1}{E_w}\begin{bmatrix} 1 & -v \\ -v & 1 \end{bmatrix}\begin{Bmatrix} \dot{\tau}_1 \\ \dot{\tau}_2 \end{Bmatrix} \tag{2}$$

$$\left\{\dot{\varepsilon}^{(p)}\right\} = \begin{Bmatrix} \dot{\varepsilon}_1^{(p)} \\ \dot{\varepsilon}_2^{(p)} \end{Bmatrix} = \frac{\dot{\tau}_e}{\tau_e}\frac{E_w - E_t}{E_w E_t}\begin{bmatrix} 1 & \dfrac{-R}{1+R} \\ \dfrac{-R}{1+R} & 1 \end{bmatrix}\begin{Bmatrix} \tau_1 \\ \tau_2 \end{Bmatrix} \tag{3}$$

$$\tau_e = \left(\tau_1^2 + \tau_2^2 - \frac{2R}{1+R}\tau_1\tau_2\right)^{1/2} \tag{4}$$

In the above expressions, E_w, E_t, v and R are Young's modulus, the tangent modulus, Poisson's ratio and the anisotropic parameter of the workpiece, respectively. The radial and circumferential components of the Kirchhoff stress are represented by τ_1 and τ_2, while τ_e is the effective stress. The uniaxial stress–strain relationships are assumed to satisfy the following relationship:

$$\tau = E_w\varepsilon \quad \text{for } \tau \le \tau_y, \qquad \tau = K\varepsilon^n \quad \text{for } \tau > \tau_y \tag{5}$$

where K is the shear strength coefficient, n the strain-hardening exponent and τ_y is the yield stress. The virtual work principle can be written as

$$\int\int_{-h_0/2}^{h_0/2} (\tau_1\delta\dot{\varepsilon}_1 + \tau_2\delta\dot{\varepsilon}_2)d\xi dA_0 = \int (f_h\delta\dot{u} + f_v\delta\dot{w})dA_0 \tag{6}$$

where h_0 is the initial sheet thickness, dA_0 denotes the undeformed differential area, ξ the initial distance from mid-surface, f_h and f_v are the force components per unit undeformed sheet area in the horizontal and vertical direction and δ the variation. By substituting the strain-displacement equations and constitutive equations into the linearized form of the equation, the general matrix form can be summarized as

$$K^{\tan g}\dot{U}_n = \dot{F} \tag{7}$$

where

$$K^{\tan g} = \int\int_{-h_0/2}^{h_0/2} N^T[B^T D_m B + \tau_1 K^{(1)} + \tau_2 K^{(2)}]Nd\eta dA_0 \tag{8}$$

N represents the shape function, B is the geometric matrix, D_m is the material matrix, and $\dot{F}$ is the node force rate, respectively. The linear shape function is used. The approximation of the tangential matrix will be corrected to satisfy the equilibrium in every step.

2.2. Lubrication/friction analysis of deep drawing process

If the roughness of the surface is significant when compared with the mean lubricant film thickness, then an appropriate governing equation of the lubricant film is the one proposed by Wilson and Marsault average Reynolds equation [7]:

$$\frac{\partial}{\partial r}\left(\frac{r\phi_r h_t^3}{12\eta}\frac{\partial p_b}{\partial_r}\right) = \frac{\partial}{\partial_r}\left[\frac{ur}{2}(h_t + R_q\phi_s)\right] + r\frac{\partial h_t}{\partial t} \tag{9}$$