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A study on variable friction model in sheet metal forming with advanced high strength steels

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ABSTRACT

Conventional Coulomb model assumes constant friction coefficient in sheet metal forming simulation. It tends to predict too high friction shear stress in forming advanced high-strength steels (AHSS). Study is conducted by firstly designing an experiment method to develop a pressure-dependent variable friction model for DP780 AHSS sheet sliding against DC53 cold-work tool. The model is then used to simulate the forming and springback of U-shape bending under tension. Comparison of the predicted results with (i) pressure-dependent variable friction model, (ii) constant friction model, and the result of experimental verification indicates significant improvement of springback prediction with the proposed model.

1. Introduction

Coulomb friction model has been commonly used to describe friction condition in the simulation of sheet metal forming (SMF) over the past few decades [1,2]. In numerical simulation of SMF process, braking shear stress (i.e. friction shear stress) to resist relative sliding between two interfacial surfaces generally varies proportionally with interfacial contact pressure and friction coefficient. Although braking shear stress is commonly applied on those effective sliding-sheet nodes, its use tends to generate huge amount of computable variables and involves with substantial computing time. Effective reduction of these computable variables in the simulation with finite element method (FEM) is achievable by assuming constant friction coefficient throughout the numerically iterative process. Theoretically, the validity of such constant coefficient law is only possible when the increase in true contact area is directly proportional to its counterpart of contact pressure – this is a specific condition only occurring under the case of elastic deformation with contact pressure below yield stress limit. However, practical SMF process usually involves with plastic deformation. From the initiation of plastic deformation onwards, further deformation usually involves with larger increment of the applied normal force than that of the true contact area. This is because the true contact area is often constrained within the geometry of its nominal counterpart. Under such condition of continually changing contact pressure to higher level, the model of constant Coulomb friction is likely invalid to be applied because braking shear stress on individual sliding nodes is impossible to exceed the shear strength of a deformed sheet. Hence, the workable/applicable shear stress is usually limited to the shear yield strength of the braked material [3]. When a greater shear stress is applied by a brake, it would susceptibly lead to (i) permanent plastic deformation of the material; and/or (ii) the material to be shorn off in the contacting zone. As a result, sliding surfaces are submitted to a combined mode condition of elastic and/or plastic contact. This type of contact complicates the friction condition because it varies with: (i) the resultant of elastic and/or plastic deformation of the two sliding materials; (ii) the nature of material tearing and shearing; and (iii) the characteristic of material transfer from soft sheet to hard tool, etc. More prominent complexity is sometimes observed in the case of forming high strength steel sheets since their higher strength generally requires much larger forming tonnage to deform or to shear when they are compared to their mild steel counterparts. Such complex circumstance tends to furnish with too high friction shear stress value if constant Coulomb friction model is used to calculate friction shear stresses. Searching for a better model to predict such shear stresses relatively closer to realistically reliable values is essential, which subsequently forms the motivation of the current research.

Appreciating the advantages of high-strength and lightweight alloys subsequently leads to the increasing use of aluminum, magnesium, and advanced high-strength steels (AHSS) as materials for auto-body panels and structures. The use of such alloys in automobile body beneficially accomplishes better fuel efficiency,

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and satisfies the environmental friendliness and safety concerns [4,5]. As compared with aluminum and magnesium alloys, the relatively lower cost and higher strength of AHSS sheet material makes it a better choice of material for structural components such as front/rear rails, A/B pillars, and door beams, etc. However, AHSS generally has lower formability [6], higher level of die wear [7], and higher level of springback [8,9] when it is compared to mild steels. Such relatively adverse forming behaviors are mainly because AHSS has higher surface hardness and higher yield strength than mild steels [10]. Hence, plastic forming of AHSS requires high interfacial pressures between tool and workpiece [11]. In a study of parallel strip drawing, Kirkhorn et al. [12] showed that the increasing of normal load gave tendency of lower friction coefficient. Furthermore, our previous study [13] also suggested that higher normal load between the deforming sheet and the forming die tended to trigger higher level of work-hardening in dual phase (DP) matrix. Such work-hardening dual phase matrix subsequently led to decreasing the values of friction coefficients with increasing loading. Results of the studies in [12,13] suggest that higher interfacial pressure tends to result in lower friction coefficient.

Most available numerical modeling of SMF assumes constant coefficient of friction. Typical examples include (i) the theoretical models proposed by Mahdavian and Shao [14] for analyzing hydrodynamic lubrication of sheet metal forming operations; and (ii) the analytical model developed by Yang [15], which was combined with elastic–plastic membrane finite element code of deep drawing, specifically for investigating full film lubrication in deep drawing. In the works of Mahdavian and Shao [14] and Yang [15], surface topography and asperity contact have not been considered because of their assumption of working in thick film regime. However, more realistic friction models usually treat the influence of roughness on the flow of lubricant and on the contact of asperities between sheet-die in SMF as boundary lubrication conditions. Consequently, many variable friction models have, in recent years, been developed to study the effect of different factors on friction behavior. Wilson et al. [16] developed a model by taking into account of different lubrication regimes in sheet-tooling interface. The model was also coupled with a finite element program for predicting friction behaviors in lubricated sheet metal forming operations. Haluk et al. [17] related the drawing parameters of sheet metal to the local lubrication condition during deformation by suitably integrating a variable friction model with a finite element program. The numerical results of the model for their sheet metal drawing process gave data closely agreeable with their experimental counterparts. Through study of the influence of bulk plastic strains on real contact areas, Wiklund et al [18] developed a model for sheet metal forming operations by improving the FE simulations originally using classical Coulomb's friction model. Although the variable friction models in [16–18] generally involved with the prediction of various process data in sheet metal forming, the models are normally not adequate for predicting the friction coefficients, which are likely changing with the variation of contact pressure in the forming of AHSS.

Accurate numerical simulation of springback in SMF of AHSS is a critical issue since it facilitates: (i) the preparation of geometry and dimension of a raw blank-piece/part; and (ii) the design of the corresponding tools for manufacturing of the part. There are many diverse efforts made for accurately evaluating springback. For example, Chen et al. [19] developed a kinematic hardening model by suitably describing the behavior of non-saturated cyclic hardening to predict springback in DP sheet metals. Rahul and Haldar [20] used an approach of finite element analysis to study the effect of hardening behavior and anisotropy on springback of Numisheet-2005 bending benchmark. Furthermore, Zang et al. [21] used material constitute technique to model springback by adequately considering Bauschinger effect and transient behavior, permanent softening, and unloading modulus of the blank. Besides the material modeling, different numerical calculation methods were also investigated by many researchers in order to predict springback. Narkeeran and Michael [22] demonstrated the use of an explicit approach to acquire implicit sequential solution for predicting springback in deforming sheet metal. Chatti [23] calculated finite strains by the use of an elastoplastic (EP) formulation instead of the commonly available hypoelastoplastic (HEP) formulations. The use of his formulation allowed accomplishing accurate springback results with significantly shortened simulation time. However, the use of variable friction models to predict springback is still hardly found in the existing literature.

The mechanism of springback when the operating die is removed is basically considered to be stress-driven. Physically, the induction of springback is mainly due to elastic strain recovery of a material during the releasing of deformation loads. Hence, the magnitude of springback can also be determined by the level of residual stresses in a formed sheet-piece. Friction coefficient is a variable for determining the magnitude of friction shear stress in a forming process. It thus significantly influences the level of residual stress and springback of a deforming workpiece. Hence, the suitable incorporation of an accurate or near realistic pressure-dependent variable friction model, into the relevant numerical simulation study of springback behaviors in forming of sheet metal, especially in forming AHSS with large springback, is important and necessary.

Aiming at more accurately predicting the springback, a numerical study with variable friction model for SMF process is conducted. This paper is presented with: (i) pin-on-disc testing results to verify the validity of ideas of variable friction coefficients in the interface between tool and workpiece, under different applied pressures (Section 2); (ii) the forming and springback results for SMF of U-shape bending under tension (BUT) (Section 3), which are predicted with the use of (a) three levels of constant friction coefficient, and (b) pressure-dependent variable friction coefficients, respectively – it further compares the predicted results with their experimental counterparts; (iii) discussion of the results (Section 4); and (iv) the outline of concluding remarks (Section 5).

2. Testing of variable friction

2.1. Materials and tester

As-received bare 0.9 mm thick DP780 AHSS sheet was used as the tested specimens while cold-worked DC53 tool steel was used to make the friction tool. The DP780 AHSS sheet had mechanical properties as shown in Table 1, and the chemical composition of cold-worked DC53 tool steel was as C 0.96%, Cr 8.12%, Si 0.95%, Mo 2.07%, V 0.17% and Mn 0.38% (mass%).

Table 1
Mechanical properties of the as-received bare DP780

Young's module E (GPa)	Yield strength σ_S (MPa)	Tensile strength σ_b (MPa)	Hardening exponentn	Hardening coeff. K (MPa)	Poisson's ratio μ	Lankford coeff.		
						R_0	R_{45}	R_{90}
205	505	785	0.161	1195	0.3	0.75	0.95	0.85