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Constitutive and friction modeling for accurate springback analysis of advanced high strength steel sheets

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ABSTRACT

The present work aims to analyze the influences of the material and friction models and to suggest the optimum selection of the models for springback simulations. Firstly, a transformation-induced plasticity (TRIP) steel was characterized using the conventional and advanced models for the springback prediction in U-draw/bending. A special attention was paid to the friction model, which was derived based on the macroscopically observed frictional behavior and interpreted with the microscopic contact mechanism. The combination of advanced constitutive and friction models could predict springback and punch load quite well. It was found that the hardening law and elastic unloading modulus had the major influences, while the friction model also had a major influence in the case of high blank holding force. A specific value of constant friction coefficient could provide similar predictions as the variable friction coefficient, but the former could not describe a non-uniform distribution of friction coefficient. Next, the analysis was extended to the sensitivity studies that considered wider ranges of material and frictional behaviors. These studies suggested that (1) the plastic anisotropy has to be modeled using an anisotropic yield function if the yield stresses or r-values affecting the relevant stress state are far from the isotropic assumption; (2) the reverse loading behavior has to be characterized using a hardening model that can precisely describe the transient hardening and permanent softening; (3) the elastic modulus should be defined using an advanced model if the material shows a visible reduction of elastic modulus; and (4) the friction coefficient should be carefully defined using an advanced friction model if the blank holding force is high.

1. Introduction

Advanced high strength steels (AHSS) are highly promising materials for lightweight vehicle structures. However, their practical application has been hindered by technical challenges such as springback. This phenomenon refers to the elastic recovery and undesirable shape changes of a formed part when it is released from the tools. In order to control or compensate for springback, the manufacturing process needs to be modified through successive trials, which usually lead to an enormous

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increase of development cost and time. For this reason, numerical methods for accurate springback prediction have become increasingly needed.

The development of numerical analyses for springback predictions has been mainly relying on the finite element (FE) technique and constitutive modeling over the last few decades. A review of these topics can be found in Wagoner et al. (2013). The role of the constitutive model is especially important for AHSS sheets, which exhibit characteristic features during deformation under reverse loading, for instance, the Bauschinger effect, transient hardening and permanent softening. Because the conventional isotropic hardening model cannot describe such phenomena, kinematic hardening and other types of models have been generally recommended for the prediction of springback (Carvalho Resende et al., 2013; Clausmeyer et al., 2014; Geng and Wagoner, 2000; Lee et al., 2012b, 2005; Shi et al., 2014; Vladimirov et al., 2009; Yoshida and Uemori, 2003). Another major characteristic of AHSS is the nonlinear and history-dependent elastic modulus. In order to capture these features, nonconventional elasticity models such as strain-dependent chord modulus or quasi-elastic-plastic models have been preferred (Eggertsen and Mattiasson, 2009; Eggertsen et al., 2011; Lee et al., 2013a; Sun and Wagoner, 2011).

Despite its great influence on springback, the frictional behavior has been often simplified in numerical simulations by adopting the classical Coulomb's law. The frictional behavior is in fact very complicated, as it is influenced by many factors such as the material and lubricant properties, process condition and environment (see Table 1). Experimental observations have revealed that the friction coefficients of sheet metals normally range between 0.1 and 0.2 in lubricated forming conditions (Felder and Samper, 1994; Gong et al., 2004; Keum et al., 2004; Saha and Wilson, 1994). Even this amount of deviation can significantly change the predicted springback; for instance, the sidewall curl changed about 24% in U-draw/bending according to Lee (2011). The sensitivity study shown in Hora et al. (2011) also implies that the friction coefficient is the major factor influencing the simulation accuracy. Therefore, a reasonable description of frictional behavior is essential in developing a reliable springback prediction model.

In sheet metal forming, the most common and practical way of estimating the friction coefficient is by numerical optimization of the punch force-displacement or draw-in length. Because this method does not require additional equipment for the friction test, it has been frequently used in both industry and academia. However, the calculated force-displacement data depend not only on the friction model but also on the constitutive model. For instance, isotropic hardening leads to higher punch force than kinematic hardening because the former predicts higher reverse yield stress than the latter. This implies that the friction coefficient can be accurately estimated only if a proper constitutive model is used. Therefore, this method is not reliable if the performance of the constitutive model is questionable and, thus, needs to be validated through simulations.

Furthermore, the assumption of a constant value for the friction coefficient over the entire interfaces between the blank and tools might not suitably represent the complex frictional behavior in forming processes. Several experimental reports have shown that the friction coefficient is not constant for a given set of contact bodies and lubricant but varies depending on loading condition and sliding velocity (Azushima and Kudo, 1995; Grueebler and Hora, 2009; Han and Kim, 2011; Lanzon et al., 1998). Santos and Teixeira (2008) suggested assigning different values of the friction coefficient on different contact regions in the U-draw/bending process. They defined three regions considering their distinctive contact conditions; the flat interfaces between specimen and die/holder, the rounded (corner) interface between specimen and die, and the interface between specimen and punch. However, this approach is not very convenient from a practical point of view because it is difficult to properly divide the contact interfaces for the parts having complex geometries. Therefore, it is more efficient to establish a more comprehensive model that captures the frictional behavior under a wide range of contact conditions. In this case, the conventional Coulomb friction model cannot be used anymore.

There have been a number of different approaches to construct such friction models. These may roughly be categorized into two groups, namely, micromechanical and phenomenological approaches. The former considers the fundamental mechanism of interaction between the contacting bodies and the lubricant. In general, a regime between boundary and mixed lubrications is relevant to sheet forming processes (Ter Haar, 1996). Specifically, boundary lubrication dominates the critical contact regions, such as tool corners, around which friction significantly influences the forming operations (Westeneng, 2001). In addition, the local plastic deformation resulting in sheet metal asperities, which is called ploughing effect, is also a major mechanism when a relatively high holding pressure is applied (Greenwood and Williamson, 1966). These mechanisms are embodied into micromechanical models in order to derive the restraining force and friction coefficient (Hol et al., 2012; Pullen and Williamson, 1972; Westeneng, 2001). Even though these approaches provide better understanding of frictional phenomena, they still entail some simplifications and assumptions that should be verified through independent friction tests.

Table 1
Factors influencing the frictional behavior.

Material property (blank and tool)	Surface topology (roughness, asperity shape and height distribution), hardness, elastoplastic deformation behavior
Lubricant property	Lubricant type, viscosity, amount, application method
Process condition	Contact pressure, sliding velocity
Environment	Temperature, humidity