Chapter 1: Introduction

1.1 Motivation

Sheet forming parts has become a successful and well-established process for metals, alloys, polymers, ceramics and composites. Sheet forming may be used as final products or are subjected to further processing such as trimming, laze cutting, punching, etc. In either case, high strength and good formability are important properties and determine the success of sheet forming process and possibly that of subsequent operations. Process and properties optimization have always been a major concern in industrial practice. It is usually attempted by detailed considerations of die and punch design, lubrication, and proper selection of processing. The goal is to control the deformation during forming process and ensure minimum variation of local zone, avoidance of cracking (failure), dimensional control, and elimination of defects.

The process of sheet forming is a complex non-linear problem. When a force is applied on a forming tool, a number of mechanisms become involved in the transformation of the material into a die and became a well-defined shape. Normally, the following processes are involved in a typical sheet forming process:

- elastic deformation
- plastic deformation
- elastic recovery

Under the action of these mechanisms, the sheet forming process attains a level of deformation, which usually decreases with higher strength of material. The properties of material, such as relative density and strength, are not only related to the nature of the product, but also depend on the mode and history of externally applied forces. More specifically, stress loading path affects particle deformation and development of contact areas, which in turn affects the formability and springback of final products.

Since the mid-seventies, modeling of hardening behavior has provided an effective way to understand the basic mechanisms and optimize sheet forming process. These models are typically continuum mechanics-based phenomenological models. Currently, the use of these models in the finite element analysis has been successful in predicting failure and springback in complex shaped sheet forming.

In sheet metal forming applications, the non-monotonous deformation is especially important because reverse loading is commonly observed when sheet element moves through the tool radii and draw beads. Also, when sheet parts are removed from tools after forming, material elements experience elastic unloading and spring-back. To describe the reverse loading behavior in the continuum phenomenological plasticity, there are two main approach, the first one based on kinematic hardening involving shifting of a single-yield surface and the second one involving multiple yield surfaces [1]. The simplest one in the former group is based on linear kinematic hardening proposed by Prager [2], Ziegler [3]. To add the transient behavior, the linear model was modified to nonlinear forms by Amstrong and Frederick [4] and Chaboche [5] by introducing an additional term to Prager's linear kinematic hardening model. Nonlinear and smooth deformation during loading and reverse loading were reproduced by introducing additional back stress term which makes total back stress decrease gradually with deformation. Several nonlinear kinematic hardening models based on Amstrong–Fredrick model have been emerged by introducing multiple back-stress terms [6] and [7] and translating limiting surface [8] and [9]. Two-surface models independently proposed by Krieg [10] and Dafalias and Popov [11] define the continuous variation of hardening between two yield surfaces. In the original multi-surface model proposed by Mroz [12], the predicted stress–strain curve is piecewise linear because of the constant plastic module [13]. Several multi/two-surface models have been proposed later[14], [15], [16], [17], [18], and [19] to analyze the one-dimensional cyclic behavior of solid structures at small strains. As a result, the prediction of fracture and spring-back with current models is not easy. The formation of parameters during loading and unloading, as well as the material elastic recovery may be confusing and also have a large effect on the final curve of prediction. With these in mind, the goal of this book is to make inroads on the understanding of the hardening behavior and propose a modification of hardening behavior to predict correctly the tension-compression curve in simple way. In the next section, we review the pertinent literature.

1.2 Literature review

In the past two decades, modeling and simulation play an increasingly important role in the design and optimization of sheet forming operations. The most common models are phenomenological and isotropic.

Various phenomenological hardening models, isotropic, kinematic and multi-surface, have been developed to reproduce hardening behavior of metals under various loading paths [2, 3, 12, 13, 20-24]. The simplest one, isotropic hardening model, uniformly extends a yield surface with fixed origin in stress space. The uniform extension implies that plastic deformation does not introduce further anisotropy and reduces any initial anisotropy. The isotropic hardening model can be adequate for FCC metals under monotonic loading, but it is not appropriate for materials under complex loading paths, where Bauschinger Effect or strength differential upon reverse loading is non-negligible. The isotropic hardening will introduce significant errors in the stress distribution of magnesium alloys undergone through sheet forming.

In contrast to the isotropic hardening model, a yield surface can translate in stress space with constant shape and size by a kinematic hardening model [13]. Various kinematic hardening models have been proposed to address Bauschinger Effect and cyclic plasticity [2, 4, 5]. One thermodynamical criterion for cyclic plasticity was summarized by Chaboche [5]: ‘the current state of materials depends only on the current values of observable variables (total strain, temperature, etc.) and a set of internal-state variables’.

The classical kinematic hardening model of Prager can describe some Bauschinger Effect, but without transient yield upon reverse loading [2, 24, 25]. Back stress rate was assumed to be proportional to the plastic strain rate in Prager’s model. This implies that continuous deformation encounters higher resistance than reverse loading. The main shortcoming of this model is that the stress strain relation is ‘univocal’ as a result of the assumed proportionality [5]. Another shortcoming is the inconsistency between different sub stress spaces. Ziegler model solved the problem of inconsistency, by translating the yield surface in radial directions [3].

Linearity in stress strain behavior and sharp reverse yield induced by Prager’s model were avoided by two- or multi-surface models [10, 11, 12, 20]. Only one yield surface was active at a given instant in time in the two- or multi-surface models. A large number of yield surfaces are needed to describe material behaviors in the multi-surface models, because of their piecewise linearity in stress strain behaviors. The two-surface model can predict cyclic plasticity well by introducing continuous variation of hardening modulus to translate the active yield surface, although it has its disadvantages discussed by Chaboche [5].

Based on Prager’s model, Armstrong and Frederick [4] proposed a nonlinear kinematic hardening model by introducing a recall term for back stress evolution. Chaboche [5] further developed it, by including multiple back stresses to more accurately model cyclic plasticity. Nonlinearity and smooth transient behavior upon reverse loading were reproduced by the recall term. The recall term implies that the effect of earlier plastic deformation on back stress decreases gradually with progressive deformation. This reflects the fact that microstructure from the recent deformation history contributes greater to the back-stress evolution than does the deformation occurring earlier.

More complex anisotropic hardening models have been proposed during last decade to consider microstructure evolution in steels subjected to arbitrary loading path change at moderate to large deformation [26-31]. Three internal state variables, (**S**, **P**, **X**), were introduced to describe ‘directional strength of planar persistent dislocation structures’ **S**, its polarity **P**, and back stress **X** induced by dislocation pile-ups. The evolution of these state variables was specified on the basis of experimental observations of the evolution of dislocation structure, such as depolarization and disintegration of preformed dislocation structure under reverse loading. The effect of prestrain on hardening in subsequent deformation can be predicted by this model. However, texture evolution is not considered explicitly, although initial plastic anisotropy induced by texture was incorporated in the model by a fourth-order tensor. The accuracy of model prediction at large strains would be improved by considering texture evolution.

1.3 Goals of this book

We believe that better understanding the role of hardening behavior is the key to better predict the tension-compression and compression-tension curves. The major goal of this dissertation is to give the simple way to determine correctly stress-strain curves with revered load, and then predict fracture obeyed ductile fracture criterion, therefore to provide a design tool to control and optimize the sheet forming operations. The specific goals of this study are outline below:

- In chapter 2 we identify the capabilities and limitations of phenomenological models on predicting such as the stress and strain curve evolution as well as the fracture tendency. To do this, we implemented one of the most popular phenomenological models – combined kinematic/isotropic model into finite element program (ABAQUS/EXPLICIT) and developed a robust user subroutine, which provides a useful tool to study formability of sheet forming process. After that we propose a modification of hardening law to predict correctly stress-strain curves with reverted load.
- In chapter 3, using the developed VUMAT, we analyzed, predicted fracture and optimized press formability of a door hinge.
- Incremental sheet forming for complex shape are modeled and studied with respect to the effect of parameters on incremental forming method and its improvements in chapter 4. A combination of both CAM and FEM simulation is implemented and evaluated from the histories of stress and strain value by means of finite element analysis. Then, the results, using ABAQUS/Explicit finite element code, are compared with forming limit curve at fracture (FLCF) and also ductile fracture criterion via VUMAT subroutine in order to predict and improve the forming conditions by changing process variables of tool radius, tool down-step and friction coefficient according to the orthogonal array of Taguchi's method.
- Chapter 5 contains a study of rotational incremental forming for magnesium alloy sheet. As the ductile failure criterion, the Oyane's fracture criterion via VUMAT user material based on a combined kinematic/isotropic hardening law and Johnson-Cook model is used to predict fracture at elevated temperatures which was generated by rotational tool and friction energy at the tool-specimen interface. The simulation results were used to predict forming limit curve for rotational incremental forming and study the effect of process parameters on ductile fracture value.