International Journal of Mechanical Sciences 114 (2016) 88–97

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

A model of one-surface cyclic plasticity with Lemaitre damage criterion for plastic instability prediction in the incremental forming process

Kai Jin [a,b], Xunzhong Guo [b,*], Jie Tao [b], Hui Wang [c], Naksoo Kim [a], Yanbo Gu [b]

[a] Sogang University, Department of Mechanical Engineering, Seoul 121-742, Korea
[b] College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 211-110, PR China
[c] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210-016, PR China

ARTICLE INFO

Article history:
Received 21 January 2016
Received in revised form
19 May 2016
Accepted 19 May 2016
Available online 20 May 2016

Keywords:
Mixed isotropic-kinematic hardening
Lemaitre damage model
Large plastic strain range
Cyclic loading
Incremental forming

ABSTRACT

The precise prediction of plastic deformation instabilities during the incremental forming process is quite complex because of the complex stress state and extremely large plastic strain. Until now, most elasto-plastic constitutive models are only suitable within a small strain range and describe the isotropic behavior. However, for extremely large plastic deformation under complex loading processes such as an incremental forming process, these models are ineffective and ill-conceived. This paper presents an elasto-plastic constitutive model which combines a mixed isotropic-kinematic hardening model with the Lemaitre damage model. This model can predict the Bauschinger effect, transient behavior, permanent softening and fractures over a large plastic strain range. By using explicit integration schemes, an integration algorithm of numerical implementation is proposed using simple expressions. A cyclic loading test comparison between experiments and numerical analysis is carried out to validate these models. The model is also applied to FE analysis of incremental forming. The deformation and the prediction of thickness are consistent with experimental results and thus verify the accuracy of the model.

1. Introduction

Incremental forming is a new sheet metal forming process which offers the advantages of a high potential economic payoff, rapid prototyping and small quantity production [1–5]. The basic components of the process are presented in Fig. 1: (1) a blank holder, (2) a backing plate, (3) blank sheet metal and (4) a rotating single point forming tool. The blank holder is used to clamp the sheet into a fixed position and the sheet is supported by the backing plate. The forming tool is used to form the sheet according to a pre- designed shape, using a CNC machining center to generate the path, with the drawing angle β defined as shown in Fig. 1, which is equal to the designed wall angle. During the incremental forming process, the blank sheet metal is formed by normal forces, shear forces and bending moments, so that it conforms to the hemispherical shape of the tip of the pin tool, with a contact area formed between the tool and the part of the sheet placed immediately in front of the moving tool. The states of strain and stress acting in these areas can be derived from the work-piece equilibrium conditions as long as the bending moments are neglected and the principal stresses are assumed to be the circumferential, meridional and thickness stresses [6].

When the tool comes into contact with the work-piece in the thickness direction, the inner surface is compressed and a tension force is applied to the outer surface and to the regions around the contact region. After the tool moves away, the force on the inner face will become a tension force. At the same time, the force on any regions that previously had a tension force will become a compression force when the tool makes contact. In the circumferential direction, the symmetric work-piece surface is under plane strain stretching conditions.

Most single point incremental forming (SPIF) investigations have focused on applications and the formability limits of the process. Silva et al. [5] analyzed the forming mechanisms and the limits of local necking. Centeno et al. [7] proposed a failure mechanism for SPIF and suggested suppressing local necking before fracturing to improve the formability. Hussain et al. [8,9] discovered a method to experimentally evaluate the formability of SPIF and also predict the position of local necking. Shin and Park [10] expressed the formability through FLC and evaluated the strain limits before the occurrence of local necking. Kim and Park [11] studied the factors that impact the formability. Young [12] and Hussain et al. [6] presented formulas to calculate the maximum wall angle allowable without fracturing the sheet metal. The investigations to this point have led to the conclusion that the formability of the process can be defined in terms of four major

* Corresponding author.
E-mail address: guoxunzhong@nuaa.edu.cn (X. Guo).

http://dx.doi.org/10.1016/j.ijmecsci.2016.05.016
0020-7403/

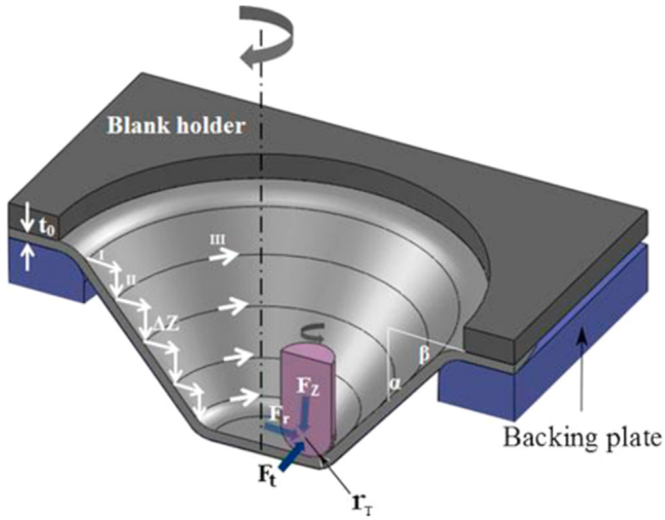

Fig. 1. Configuration of incremental forming.

parameters [2]: (1) the thickness of the sheet, (2) the size of the vertical step down per revolution, (3) the speed (both rotational and feed rate) and (4) the radius of the forming tool. Therefore, the first important task in FE analysis is accurate prediction of plastic deformation instabilities and the thickness of the sheet after incremental forming. Sawada et al. [13] proposed a deformation mechanism using 2D FE analysis. Through FEM simulation, Bambach et al. [14] highlighted that the thickness shear and the shear stress is dependent on the tool diameter and the feed speed in the depth direction. Capece Minutolo et al. [15] analyzed the formability by using LS-DYNA. Fang et al. [16] presented a deformation mechanism that determines the fracture behavior through experiments and FE analysis. Malhotra et al. [17] developed a fracture model and predicted the formability for SPIF. Eyckens et al. [18] predicted formability using the Marciniak-Kuczynski model.

All of these previous studies are focused only on fracture or formability prediction, but have not considered cyclic loading situations which cause a Bauschinger effect and result in the actual material behavior no longer being isotropic. The constitutive models proposed in this paper can be used to correctly describe the shape and thickness of the material after forming and reasonably predict the accumulation of damage.

As metals are increasingly being applied, there are many challenges that need to be faced to address the complex mechanical behavior of metals, the shape of the product and loading conditions. If the forming process undergoes large plastic deformation, this makes the design of tool and the process conditions more difficult. Numerical analysis by finite element method is an efficient tool that can be used to overcome these challenges and difficulties. However, its accuracy is the most important determinant of its usefulness. Therefore, it is both necessary and essential to establish an accurate and suitable constitutive model to describe the mechanical behavior of metals, especially under complex and large-strain deformation paths.

An extensive number of plasticity models have been proposed to accurately describe the mechanical behavior of metals. The basic model is isotropic hardening, where the yield surface will not expand under compression if the load cannot reach above the yield under tension. Therefore, it is limited for cyclic loading since it does not account for the Bauschinger effect. Kinematic hardening was proposed to address this challenge. Frederick and Armstrong [19] introduced a laxation term known as the backstress to account for metal softening under compression and thus can be used to describe the Bauschinger effect in cyclic loading. However, a single term backstress factor limits the applicability of the model to a variety of materials. Chun et al. [20] described the Bauschinger effect for sheet metal in further detail. Based on the Armstrong–Frederick model, Chaboche et al. [21,22] proposed a generalized model, which employs several independent backstresses with the same expressions but different parameter values to simulate the nonlinear behavior of different metals. However, without isotropic hardening, there are large deviations in the analysis results. Zaverl and Lee [23] proposed a combined model using nonlinear kinematic hardening and isotropic hardening rules, which can accurately describe the nonlinear behaviors of many metals. To describe metal behaviors more precisely, Zang et al. [24,25] proposed a two-term kinematic hardening model, which combines the Chaboche model and the Ziegler model.

However, for extremely large plastic deformation where the equivalent plastic strain is over 50%, these models are ineffective, since they are only accurate within a small range of plastic deformations. Currently, damage accumulation also needs to be taken into account to evaluate the metal softening effect and integrate this into a corresponding constitutive model. There are still many challenges to address to predict damage accumulation and ductile fracture during real forming process. There are currently two main approaches existing: micromechanical models and phenomenological models [26]. Within micromechanical models, McClintock et al. [27] firstly modeled the role of micro-voids in ductile failure. Rice and Tracey (R&T) [28] proposed a model by studying the growth of spherical voids until fracture and concluded that the stress triaxiality can be used to determine the growth of voids. Gurson [29] employed a void volume fraction to calculate the damage. Tvergaard and Needleman [30] then expanded the Gurson model by introducing void nucleation and void coalescence. Within phenomenological models, Lemaitre [31] proposed a model that references a consistent thermodynamic framework. Their model has been widely used and adapted for different situations. Xue [32] and, Bao and Wierzbicki (B&W) [33] considered the influence of hydrostatic pressure and the Lode angle to construct damage models that take the influence of stress triaxiality and the Lode angle into account (Fig. 2).

Therefore, this study integrates these damage models to propose one-surface plastic model which is shown in Fig. 3, which integrates a combined isotropic-kinematic hardening model and a continuum damage model and can describe the Bauschinger effect, transient behavior, the metal softening effect and damage accumulation for large plastic deformations under complex loading conditions. As shown in Fig. 3, the stress σ_T and the backstress α_T keep increasing under tension when the stress is bigger than the

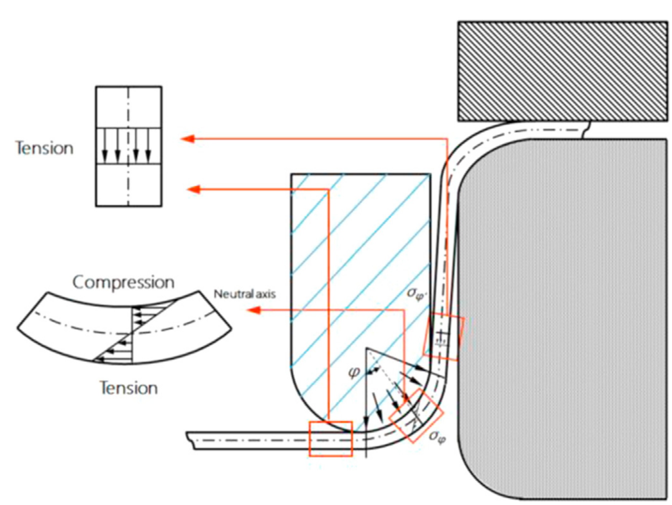

Fig. 2. Schematic representation of the details of the acting stresses in the thickness direction.