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Springback Modeling in L-bending Process Using Continuum Damage Mechanics Concept

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Abstract

Springback is one of the most common and important issues in metal forming area. Due to the fact that springback depends on a variety of parameters, it is hard to predict. Hence, in this paper, the effect of continuum damage mechanics (CDM) on springback was investigated based on the Lemaitre isotropic unified damage law. Swift's hardening law was employed to describe isotropic hardening behavior. The results indicated that considering the damage mechanics concept in springback modeling increases the predictability of springback.

Keywords: Springback prediction, Damage, Simulation, L-bending test, FEM.

1. Introduction

Metal forming is one of the vital processes in industry especially in automotive industry. Since there are large and permanent deformations in metal forming area, the governing equations are classified in plasticity subjects. One of the common and important problems in metal forming processes is a phenomenon called springback. Generally, when the loading step of a metal forming process is finished and forming tools are removed, the deformable workpiece (e.g. sheet, tube, etc.) deviates from its final desirable shape. This phenomenon is technically termed springback. Neglecting this important phenomenon leads to other problems especially during the assembly step. Thus, it is a vital subject in manufacturing process of a part. Die designers traditionally used trial and error approach to compensate for the occurrence of springback in metal forming processes. However, it was not economical as it was a time-consuming, costly process. Therefore, researchers attempted to predict springback in various metal forming processes using analytical and numerical modeling.

At first, springback prediction was carried out using analytical methods [1-2]. As computational methods progressed and new numerical methods developed, the finite element method (FEM) came to be regarded as a powerful method for the simulation of metal forming processes and springback prediction. Bauschinger effect is one of the effective parameters on springback simulation. Researchers did not consider this important issue in their studies at first; however, they began to take it into account in their next investigation [3-4]. Lee et al. [5], for instance, showed that the separate use of the isotropic and the kinematic hardening models leads to the overestimation or underestimation of real magnitude. Therefore, a combination of the hardening laws proved to be a valuable idea to improve springback prediction. Hence, Taherizadeh et al. [6] investigated springback prediction for an anisotropic material, using a mixed iso-kinematic hardening model based on a non-associated flow rule. Besides, some researchers considered the Young's modulus changes during the plastic deformation in their simulations [7-8]. It is interesting to know that the theory of classical plasticity assumes that materials have a linear unloading behavior with a slope equal elasticity modulus whereas experimental results show that the elasticity behavior in unloading is not linear, has a little curvature and depends on plastic strain [9-10]. Chatti and Hermi [7] employed the modified Yoshida-Uemori model [10] to predict the springback that improved its prediction. It seems that researchers have started to take an interest in investigating the springback by using damage concept [11-12]. For instance, Vrh et al. [12] presented a model for predicting springback by using Gurson damage model [13] and anisotropy. Hence, in this paper, the material evolution modeling based on the Lemaitre isotropic unified damage law was conducted with the aim of investigating the influence of damage concept on springback prediction.

2. The Lemaitre isotropic unified damage law

Damage means gradual decrease or sudden decadence of the mechanical strength of material due to loading, thermal and chemical effects. From a physical point of view, damage is related to plastic or irreversible strains and more generally to strain dissipation whether on the mesoscale, the scale of the representative volume element (RVE), or on the microscale. According to Fig. 1 and by introducing damage variable ($D = S_D/S$), if S_D is the area of microcracks and microvoids in the cross-section of the material and no microforce is acting on the microsurface of microcracks and microvoids surface, it is convenient to introduce effective stress ($\bar{\sigma}$) related to effective surface as:

$$\bar{\sigma}_{ij} = \frac{\sigma_{ij}}{1-D} \tag{1}$$

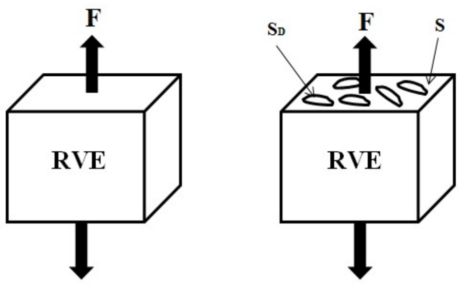

Fig.1. one-dimensional element (Left: no damage, Right: damaged)

Also, the occurrence of the damage changes the von Mises's yield function into [14]:

$$f = \left[\frac{1}{2}\frac{\sigma'_{ij}\sigma'_{ij}}{(1-D)^2}\right]^{1/2} - \sigma_y - R = 0 \tag{2}$$

which can be simplified in one dimension as follows:

$$\sigma = (\sigma_y + R + X)(1-D) \tag{3}$$

in which, X , R and σ_y are backstress, stress due to isotropic hardening and yield stress, respectively. In this case, the elasticity modulus of the damaged material is defined [14] as:

$$\tilde{E} = E(1-D) \tag{4}$$

Equations (3) and (4) as well as experiments show that damage equally decreases the yield stress, the isotropic strain hardening stress, the backstress and the elasticity modulus. Lemaitre using thermodynamics of irreversible processes presented the damage criterion as shown below [15]:

$$\dot{D} = \left(\frac{\sigma_{eq}^2 R_v}{2ES(1-D)^2}\right)^s \dot{p} \tag{5}$$

$$R_v = \frac{2}{3}(1+\upsilon) + 3(1-2\upsilon)\left(\frac{\sigma_H}{\sigma_{eq}}\right)^2 \tag{6}$$

In this equation, R_v is triaxiality function, E elasticity modulus, p accumulated plastic strain, σ_{eq} von Mises equivalent stress and σ_H hydrostatic stress. There are two material constants, namely, s and S , in equation (5) that must be defined. In general, the material constants of the Lemaitre isotropic unified damage law (s and S) must be defined by means of fatigue tests. As a result, these parameters can be calibrated by performing numerical simulations for the simple tension test. Therefore, due to shortage of experimental data for some materials in many cases for researchers, here we obtained these material constants based on the trial and error approach as given below.

The consideration of uniaxial case leads to $R_v = 1$, $p = \varepsilon_p$ which simplify the equation (5) as:

$$\dot{D} = \left(\frac{\sigma_{eq}^2}{2ES(1-D)^2}\right)^s \dot{\varepsilon}_p \tag{7}$$

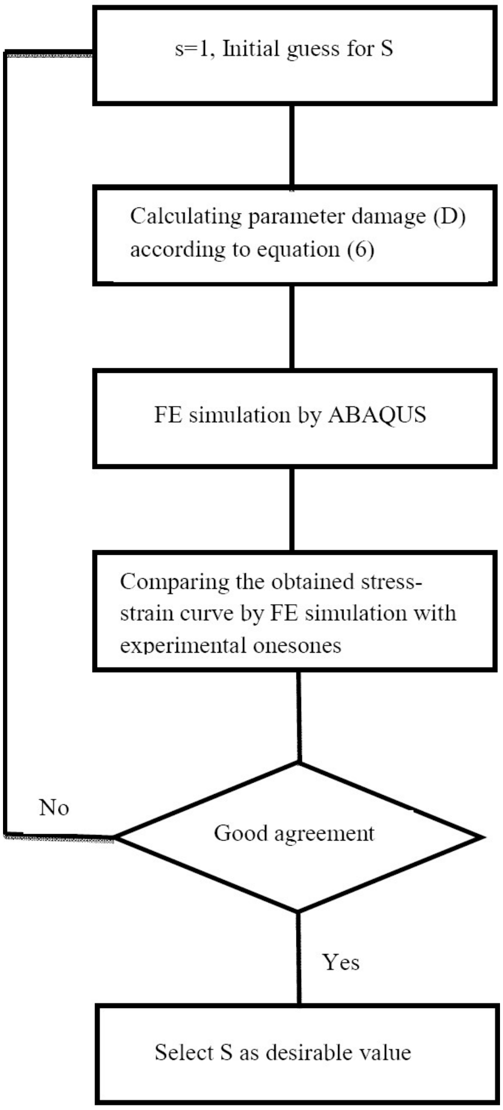

Fig.2. Flowchart for picking the damage model constants (s and S).

According to Fig. 2, the damage parameter (D) is obtained in terms of other material parameters by integrating equation (7). On the other hand, according to experimental results, the “s” material parameter is equal to “1” for the majority of materials [14]. By considering various amounts of S based on a trial and error approach and comparing stress-strain curve of simulation with experimental ones, we selected the S material parameter to be S=0.22 (MPa) as the reasonable value. The good accordance observed between experimental and simulation ones of Fig. 3 can reasonably guarantee the soundness of our decision to select material parameters.

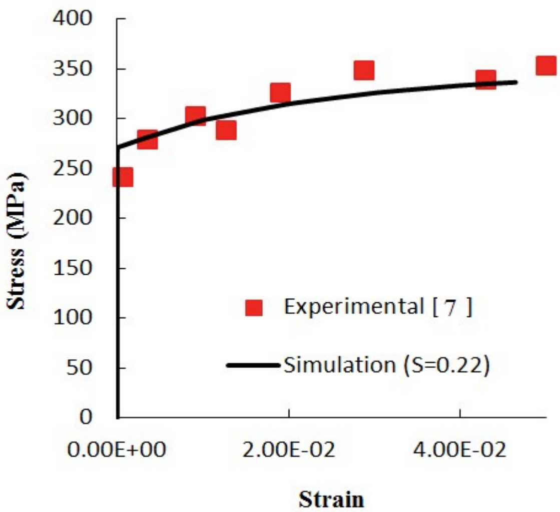

Fig.3. Stress-strain curve for s=1, S=0.22.

3. L-bending test

For our investigation, the information of an L-bending test following reference [7] was considered. The schematic illustration of this test is shown in Fig.4. In this process the sheet is placed between the die and the holder. Moving down the punch causes the sheet to undergo plastic deformation and is deformed to an L-shape part. Starting the unloading step leads to springback in the deformed sheet. In this specific L-bending test, R_p=3mm, R_d=4mm and g=0.95mm. The workpiece is a sheet which is 61.2 mm long, 11.3 mm wide and 0.8 mm in thick and whose mechanical properties are given in Table 1.

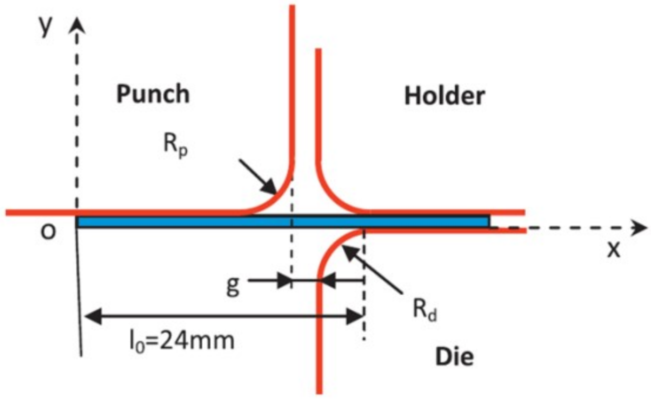

Fig. 4. Schematic illustration of L-bending test [7].

Table.1. Mechanical properties of sheet in L-bending test [7].

E=210 (GPa)	υ=0.3			
Hill's constants	F=563	G=0.43	H=0.569	N=2.04

4. Some main FE considerations

In order to simulate the L-bending test, both the forming and springback steps were solved by means of ABAQUS implicit solver. The die, the holder and the punch were treated as analytical rigid surfaces and the sheet was considered a deformable part. Due to the high ratio of the width to the sheet thickness (w/t>10), 2-D plane strain case was used in order to have a convenient modeling. Likewise, "Surface to Surface Contact" case was considered so as to describe contact behavior during the process. The contact between the punch and sheet was assumed to be frictionless but a $\mu = 0.125$ was considered to be the friction coefficient for other involved surfaces [7]. The holder and the die were constrained to be fixed during simulation of metal forming process whereas the punch moved down to make an L-shape part. When the loading step was finished, the unloading step also was simulated in order to springback modeling. The XSYMM boundary condition (U_x=R_y=R_z=0) was utilized to satisfy the boundary condition for the side of the sheet which had been placed between the holder and the die. Meinders et al. [16] reported that the use of at least ten elements to be in contact with the die radius led to an accuracy of about 1% in springback simulation. For this reason the blank was divided into three areas and the middle partition was meshed by 0.1×0.1 (mm^2) elements. Finally, the sheet was meshed using totally 1200CPE4R elements with eight elements through thickness that are 4-node bilinear plane strain quadrilateral ones. Reduced integration and hourglass control was set, too. The Swift law of $\sigma=575(0.012+\varepsilon_p)^{0.17}$ was utilized to describe isotropic hardening behavior [7].

Also, the Ziegler model is presented below according to which the evolution of linear hardening model consists of a linear translation of the yielded surface through the backstress, i.e., X. The hardening coefficients were considered as listed in Table 2.

$$\dot{X} = C\frac{1}{\sigma_0}(\sigma - X)\dot{\varepsilon}^p \tag{8}$$

C and σ_0 are the material constants which are determined from the optimization with the experimental stress – strain curve.

Table 2. Kinematic hardening constants.

C (MPa)	σ_0 (MPa)
853.1	271 MPa

5. Results and discussion

Finally, FEM simulation was carried out and the results were obtained as Table 2 by considering the all mentioned notes.

Table.3. Springback prediction using various hardening models (deg.)

Hardening model	Without damage	With damage
IH	3.63	3.22

The results show that considering CDM in springback prediction leads to the lower springback magnitudes into case that occurring of the damage mechanics due to plastic deformation did not considered. This finding can be justified as follows.

Based on the analytical approach, the springback of the sheet in L-bending process is related to $v\sigma_y/E$ [17]. On the other hand, the CDM causes a decrease in both the yield stress and the elasticity modulus (See equations (3) and (4)). Thus, the decrease of the predicted springback in the damaged material case can be related to the decrease of the ratio of yield stress to elasticity modulus due to CDM. Fig. 5 shows stress distribution within the sheet during simulation of the L-bending test. As it is observed, after the unloading step and occurrence of springback, releasing part of the elasticity strains leads to a decrease in the stress level. In fact, the releasing of elastic strains results in the springback after the unloading stage.

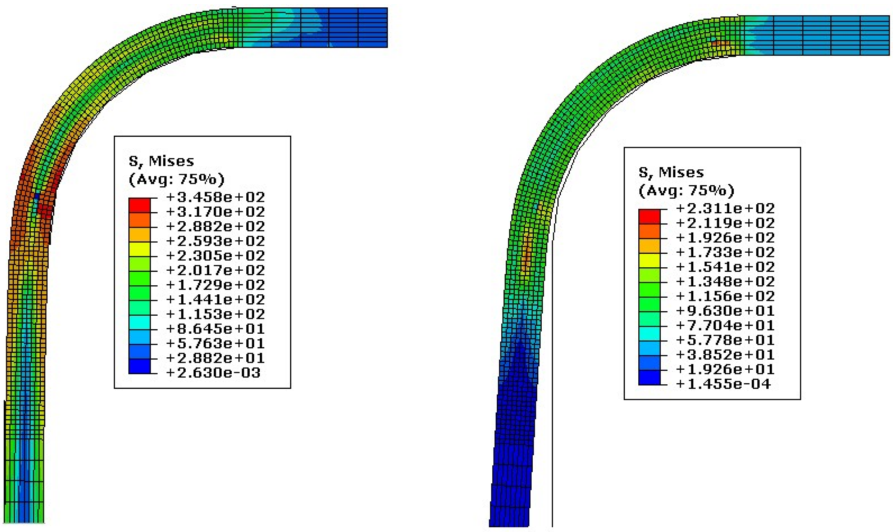

Fig.5. Distribution of von Mises stress in the blank (left: loading, right: springback)

Figs. 6 and 7 depict equivalent plastic strain distribution and scalar stiffness degradation distribution within the sheet, respectively. It can be seen from these figures that the maximum damage and scalar stiffness degradation occur at zones of height equivalent plastic strains.

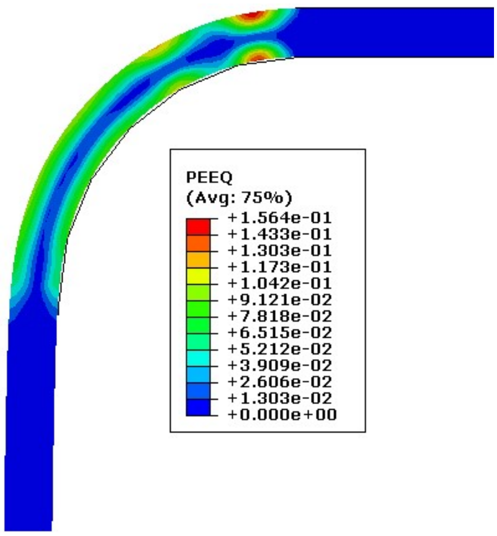

Fig.6. Equivalent plastic strain distribution

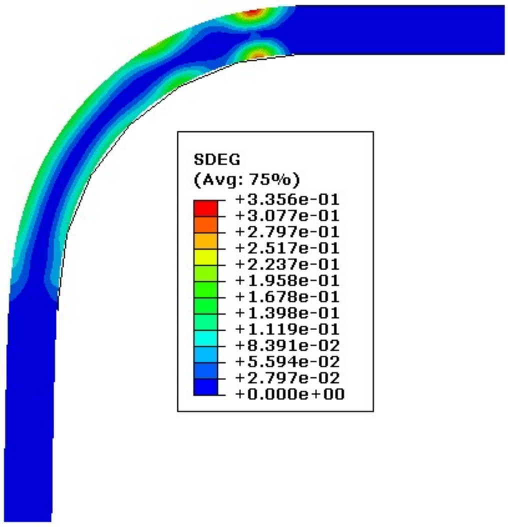

Fig.7. scalar stiffness degradation distribution

6. Summary and conclusion

In this study, the influence of considering the continuum damage mechanics (CDM) on springback prediction was investigated. To this end, the test of simulating L-bending was carried out by considering material evolution based on the Lemaitre isotropic unified damage law using ABAQUS simulation. The Swift's isotropic hardening model was utilized to describe the material hardening behavior. The results showed that considering CDM in springback modeling results in a decrease in predictability. This decrease of springback can be justified by the decrease of σy/E ratio due to damage mechanics during plastic deformation. The results also demonstrated that damage initiation and stiffness degradation happen at zones of height equivalent to plastic strains. The Lemaitre isotropic damage model does not consider the closure effect of microcracks and microvoids in compressing loading. Although it yields reasonable results for metals, it is suggested that future research studies investigate the springback prediction by means of other damage models that consider the closing effect of the microcracks and the microvoids and present more accurate evolution of material. On the other hand, it is common to conduct metal forming processes modeling with a constant friction coefficient whereas it is not constant and depends on some parameters such as velocity and pressure. Thus, modeling metal forming processes using friction describing models can be another suggestion for improving the accuracy of springback prediction.

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