Numerical study on springback prediction of aged steel based on quasi-static strain-hardening material model

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Abstract

Material model of aged steel, the material’s stress and strain behavior in the region of yielding, plays a critical role in springback prediction of FEA simulation. In most of the FEA simulations, the material is modeled as a linear elastic and then after yielding, a linear strain-hardening model or a power-law strain-hardening model. In the prediction of springback by FEA simulation, there is always a problem that the prediction is far away to the true springback of the products or samples. This paper employs a quasi-static strain-hardening material model which gives a more accurate description of the material properties of aged steel for FEA simulation of the forming. A typical V-bending for aged steel is simulated with finite element software, ABAQUS, to predict the springback. A 2D model which consists of multiple rigid bodies and a deformable body is performed in this study adopting four-node linear plane-strain elements. Meanwhile, a 2D model that applies a power-law strain-hardening material model is implemented as a contrast. By comparing the results from the simulations based on different material models with those from experiments, a better correlation between the simulations using a quasi-static strain-hardening material model and the experiments is achieved. Besides, the bending process for aged steel is also analyzed utilizing quasi-static strain-hardening material model with variable ageing coefficients. It is drawn that the greater the ageing coefficient within certain range, the greater the springback simulation accuracy by comparison between simulation and experiment results. In addition, as the upper yield stress is not easy to be measured directly, a method for reverse calculation of upper yield stress through springback ratio and quasi-static flow stress is proposed.

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Keywords: Springback; FEA; V-bending; Aged steel; Ageing coefficient; Reverse calculation

1. Introduction

Springback is a common phenomenon during the process of metal forming, which is caused by the elastic recovery after unloading. It brings error into the designed shape of the formed part as the radius of curvature of material increases after the internal stress is gradually released during the unloading phase. In order to obtain high dimension accuracy of formed products or samples, spring-back prediction of FEA simulation is carried out for die design and compensation. A finite element model was developed by Hamouda et al. [1] to analyze the bending process and springback phenomena of different grades of stainless steel material with computed punch load-displacement curves, von Mises stress and plastic strain presented and discussed. Nilsson et al. [2] adopted the finite element method to study springback for eight different materials of varying thickness and compared the results from the simulations with those from experiments. Li et al. [3] analyzed the effect of the material-hardening mode on the spring-back simulation accuracy of V-free bending by using a self-developed 2D elasto-plastic finite element program.

Springback is primarily affected by geometrical parameters of dies, material models of sheets, friction conditions between sheets and dies, etc. And the material model, the material’s stress and strain behavior in the region of yielding, plays a more critical role in springback estimation than other factors aforementioned.

The material model for FEA simulation is hard to be accurately deduced from a tensile test as the stress-strain relationship is very complicated when the material begins to deform plastically. Thus, for the convenience of actual application, some simplified material models and relevant empirical equations have been put forward. In most of the FEA simulations, the material model for aged steel is described as a linear elastic and then after yielding, a linear strain-hardening model or a power-law strain-hardening model which causes a problem that the prediction of spring-back by FEA simulation is far away to the true springback of the aged steel products or samples.

In this paper, a series of V-bending finite element models with bending angles from 60º to 120º and bending curvature radii from 30 to 120 mm are established to study the springback prediction of aged steel employing quasi-static strain-hardening material models with ageing coefficients from 1.1 to 1.5.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>YPE</td>
<td>Yield point elongation</td>
</tr>
<tr>
<td>E</td>
<td>Young’s modulus</td>
</tr>
<tr>
<td>ε</td>
<td>Strain</td>
</tr>
<tr>
<td>σ</td>
<td>Stress</td>
</tr>
<tr>
<td>ε_s</td>
<td>Strain at the yield point</td>
</tr>
<tr>
<td>σ_s</td>
<td>Stress at the yield point</td>
</tr>
<tr>
<td>K</td>
<td>Hardening coefficient and</td>
</tr>
<tr>
<td>n</td>
<td>Hardening exponent</td>
</tr>
<tr>
<td>σ_u</td>
<td>Upper yield stress</td>
</tr>
<tr>
<td>σ_l</td>
<td>Lower yield stress</td>
</tr>
<tr>
<td>σ_E, ε_E</td>
<td>True stress and strain</td>
</tr>
<tr>
<td>σ_T, ε_T</td>
<td>True stress and strain</td>
</tr>
<tr>
<td>σ_f</td>
<td>Low stress</td>
</tr>
<tr>
<td>λ</td>
<td>Ageing coefficient</td>
</tr>
<tr>
<td>ν</td>
<td>Poisson ratio</td>
</tr>
<tr>
<td>r</td>
<td>Punch head radius</td>
</tr>
<tr>
<td>α</td>
<td>Angle formed</td>
</tr>
<tr>
<td>r</td>
<td>Bending curvature radius</td>
</tr>
<tr>
<td>Δθ</td>
<td>Springback angle</td>
</tr>
<tr>
<td>θ_1</td>
<td>Bending angle before springback</td>
</tr>
</tbody>
</table>
2. Aged steel and its material model

2.1. Introduction to aged steel

Aged steel refers to low-carbon steel which ages during heat treatment or naturally at room temperature to ensure an aggregate of crucial mechanical and physical properties, for example, high strength. The characteristic of ageing is manifested by an increase in the stress where plastic deformation starts; plastic deformation then proceeds in an inhomogeneous manner during the yield point elongation zone and after that, uniform strain-hardening deformation begins up to the maximum stress. Fig. 1 shows the engineering stress-strain curve of an aged steel sample from the tensile test.

![Fig. 1. Engineering stress-strain curve of aged steel from tensile test.](image)

In tensile test, it is possible for yield point elongation zone to exist between zones of elastic and plastic deformation, while in bending, if it is assumed that plane sections of the sample keep plane and rotate during bending process, then the yield point elongation zone will be not in existence any more [4]. Therefore, the true stress-strain curve for bending can be depicted as shown in Fig. 2.

![Fig. 2. True stress-strain curve of aged steel for bending.](image)

As can be seen from Fig. 2, plastic deformation starts at the upper yield stress and after that, the stress sharply drops to the quasi-static flow stress at which uniform strain-hardening deformation occurs. The area of the curve below the lower yield stress can be obtained by back-extrapolation.
2.2 Material model of aged steel

A quasi-static strain-hardening material model deriving from Fig. 2 is used for FEA simulation, which is as follows:

\[
\sigma = \begin{cases} 
E \varepsilon & (\varepsilon < \varepsilon_s) \\
\sigma_f & (\varepsilon = \varepsilon_s) \\
K \varepsilon^n & (\varepsilon > \varepsilon_s)
\end{cases}
\]  \hspace{1cm} (1)

In the region of elastic deformation, the stress infinitely approaches \(\sigma_u\) as the strain approaches \(\sigma_s\). The \(\sigma_f\) is assumed to be the initial yielding stress and the extent of ageing is represented by \(\lambda = \sigma_u/\sigma_f\). The previous work [4] suggests that local creases or kinks may form in the product or sample when \(\lambda\) is more than or equal to 1.5. Thus, in order to avoid kinking, it is of great significance to keep \(\lambda\) less than 1.5 during ageing process.

Two kinds of samples that have deep ageing effects are chosen for the study, which are marked as SA and SB respectively; some basic parameters of these two materials are given in Table 1, where \(\sigma_s\) is the yielding stress as received, namely without ageing effects.

<table>
<thead>
<tr>
<th>Material</th>
<th>(E) (GPa)</th>
<th>(v)</th>
<th>(\sigma_s) (MPa)</th>
<th>(K) (MPa)</th>
<th>(n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA</td>
<td>202</td>
<td>0.3</td>
<td>246</td>
<td>1125</td>
<td>0.226</td>
</tr>
<tr>
<td>SB</td>
<td>143</td>
<td>0.3</td>
<td>356</td>
<td>504</td>
<td>0.08</td>
</tr>
</tbody>
</table>

3. Finite element modeling of V-bending for springback prediction

The commercial FEA software package, ABAQUS 6.12, is used to predict springback. All the models are performed in 2D since plane-strain conditions are assumed according to the actual sample situations where the lengths of the samples, the \(z\)-coordinate directions, are very large in comparison with the dimensions of the samples in the other two directions.

The schematic view of the V-bending process is illustrated in Fig. 3, where \(r\) is the punch head radius and \(\alpha\) is the angle formed. The punch and the die are treated as rigid bodies and they are in contact with the sample that is a deformable body and meshed with four-node linear plane-strain elements. The sharp corners of the rigid bodies are rounded so as to prevent them from penetrating into the deformable body.

Fig. 3. Schematic view of V-bending.
Two groups of V-bending finite element models were set up. In group A, the bent sample’s included angle, $\alpha$, changes from 60º to 120º while the bending curvature radius, $r$, keeps constant; in group B, $r$ varies from 30 to 120 mm while $\alpha$ remains unchanged.

4. Results and analyses

The simulation result of V-bending with $\alpha$ equal to 90º, $r$ equal to 1 mm and $\lambda$ equal to 1.1 is given in Fig. 4. The springback angle, $\Delta \theta$, is defined as $\theta_1 - \theta_2$, where $\theta_1$ is the bending angle and $\theta_2$ the bending angle after springback.

A power-law strain-hardening material model was employed as a contrast in both groups. The effect of bending angle on springback ratio is analyzed in Section 4.1 while the impact of bending curvature radius on springback angle is discussed in Section 4.2. A method for reverse calculation of upper yield stress is proposed in Section 4.3 in accordance with the simulation results from group A.

4.1. Effect of bending angle on springback ratio

The springback ratio, $k$, is defined as the springback angle over the bending angle and is plotted versus bending angle in Fig. 5 on the basis of the simulation outcomes from group A and experiment data using sample SA.

As can be seen in Fig. 5, the springback ratio for the experiment firstly decreases from the peak of about 13.7% to the trough of around 11.2% and then slightly increases to approximately 11.6% at the bending angles of 60º, 90º and 120º separately. Also, the simulation applying quasi-static strain-hardening material model gives better correlation with the experiment than that adopting power-law strain-hardening material model and the greater the ageing coefficient in quasi-static strain-hardening material model, the greater the springback prediction accuracy, especially for sample SA having deep ageing effects.

4.2. Impact of bending curvature radius on springback angle

Fig. 6 shows the relationship between the springback angle and the bending curvature radius in the light of the simulation results from group B and experiment values utilizing sample SB.

It can be found out from Fig. 6 that the springback angle for the experiment ascends with rising bending curvature radius, from the valley of around 5º to the summit of about 20º, and the discrepancy between the simulation outcomes with each material model and the experiment results goes up when the bending curvature radius increases. As sample
SB has deep ageing effects, the simulation results utilizing quasi-static strain-hardening material model with ageing coefficient of 1.3 are closest to the experiment measurements while the power-law strain-hardening material model brings in maximum error in predicting springback of deeply aged steel.

4.3. Method for reverse calculation of upper yield stress

In practice, it is not easy to measure the value of upper yield stress as it is a transient and then rapidly falls to the quasi-static flow stress.

For the quasi-static flow stress is relatively easy to be measured, the upper yield stress can be back-calculated by \( \sigma_u = \lambda \cdot \sigma_f \), where \( \lambda \) can be estimated through simulation.

The relationship between springback ratio and ageing coefficient is shown in Fig. 7 based on the simulation outcomes with \( R \) equal to 90° and \( r \) equal to 1 millimeter. If an ageing steel has the same material properties as sample SA and satisfies the bending conditions described above, then the ageing coefficient is able to be reckoned by calculation of springback ratio. As the red dashed lines in Fig. 7 indicate the ageing coefficient falls at 1.4 when the springback ratio goes to 11%. According to this principle, a database for aged steels with various material properties can be built; ageing coefficient can be acquired by accessing the database after the springback ratio is input, and then the acquisition of upper yield stress becomes no longer difficult.

![Fig. 5. Springback ratio vs. bending angle for sample SA.](image)

![Fig. 6. Springback angle vs. bending curvature radius for sample SB.](image)
Fig. 7. Relationship between springback ratio and ageing coefficient for sample SA, $R = 90^\circ$, $r = 1$ mm.

5. Conclusions

This paper has studied and analyzed the springback of aged steel based on V-bending simulation and experiment results. It can be concluded that using quasi-static strain-hardening material model for aged steel to predict the springback gives more accurate outcomes than other material models, especially for the materials having deep ageing effects. Therefore, it needs to be addressed that in other simulations that material having some aging effects, using an improper material model will lead to error in springback prediction.

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