Springback prediction of titanium tube bending considering Bauschinger effect and Young's modulus variation

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Abstract. High strength titanium bent tubes present promising usages in advanced aircraft and spacecraft to achieve lightweight and improve overall performance. However, the high ratio of yield strength to Young's modulus results in significant springback in bending, which limits their forming accuracy. In this work, the Bauschinger effect and nonlinear unloading behavior of high strength Ti-3Al-2.5V tube are experimentally investigated. Then, to describe such behaviors, the Yoshida-Uemori (Y-U) two-surface hardening model and Chord unloading model are introduced into the elastoplastic constitutive framework and numerically implemented. Taking rotary draw (RDB) bending as a case, the springback angles are predicted and analyzed by comparison with the experimental results.

1. Introduction

Titanium alloy tubes are increasingly used for hydraulic pneumatic, fuel and environment control systems in advanced aircraft and spacecraft as bleeding components owing to their high specific strength and corrosion resistance capability [1]. As typical high strength titanium tube (HSTT), stress relieved Ti-3Al-2.5V tube can meet the aeronautic product requirements of high-pressure resistance, mass reduction and fuel economy, attracting increasing attention in aircraft manufacturing industry. During titanium tube bending, when the multi-tools are removed, more pronounced springback inevitably occurs due to its high ratio of the yield strength to Young's modulus. The springback reduces the accuracy of the bent tubular parts, and decreases the connection/sealing performance with other parts as well as the internal structure compact. Thus, it is particularly important to achieve for high precision bent tubes in the aeronautic "bleeding" tube system and the precision springback prediction should be considered as a key issue in HSTT bending.

The accurate springback prediction strongly depends on the accurate description of the Bauschinger effect and the nonlinear unloading behavior [2]. To take the Bauschinger effect into consideration in the forming-unloading deformation analysis, Yoshida and Uemori proposed a two-surface isotropic-kinematic hardening model, called Yoshida-Uemori (Y-U) model [3], which has been widely used for improving springback prediction accuracy in high strength steel sheets forming. Also, to describe the nonlinear unloading behavior, the Chord model was proposed, which is a linearly-approximated stress-strain gradient during unloading and demonstrated that the unloading modulus gradually decreases with plastic deformation [3].

However, for the titanium tubes, both of the above two behaviors still remain unclear and have been seldom found in springback studies. For improving the accuracy of springback prediction in HSTT bending, it is essential to clarify the Bauschinger effect and nonlinear unloading behaviors, and take them into consideration in springback prediction.

In this study, we attempt to experimentally clarify the Bauschinger effect and nonlinear unloading behaviors in HSTT. Then, an elastoplastic constitutive frame work, considering the above two material behaviors, was established and numerically implemented. Taking RDB as a case, the springback angles were predicted and analyzed by comparison with the experimental results.

2. Materials behaviours

2.1. Bauschinger effect

HSTT of stress relieved Ti-3Al-2.5V tube, with Φ=12 mm and t=0.9 mm, was used in this study. By uniaxial tension test, the mechanical properties, including elastic modulus, yield strength, tensile strength were obtained. To observe the Bauschinger effect in HSTT, the cyclic tension-compression test was carried out. This test was modified from the ASTM standard with a special tube specimen design for overcoming the bucking. Figure 1 shows the designed specimen with the gauge length of 2 mm and the projection width of 2 mm. To accurately measure the deformation between such a small gauge length, the DIC optional measurement instrument was applied. Figure 3 (a) shows The tension-compression stress-strain curves, indicating that the Ti-3Al-2.5V tube is strongly susceptible to the Bauschinger effect.

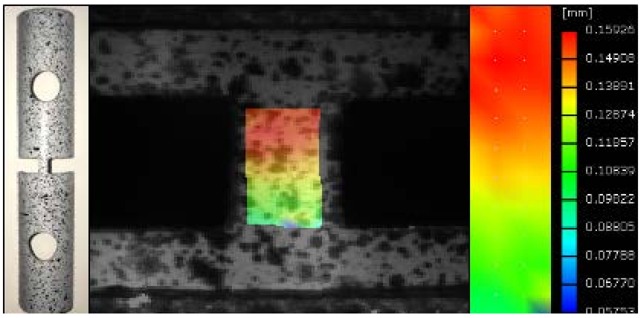

Figure 1. Specimen design and DIC measurement

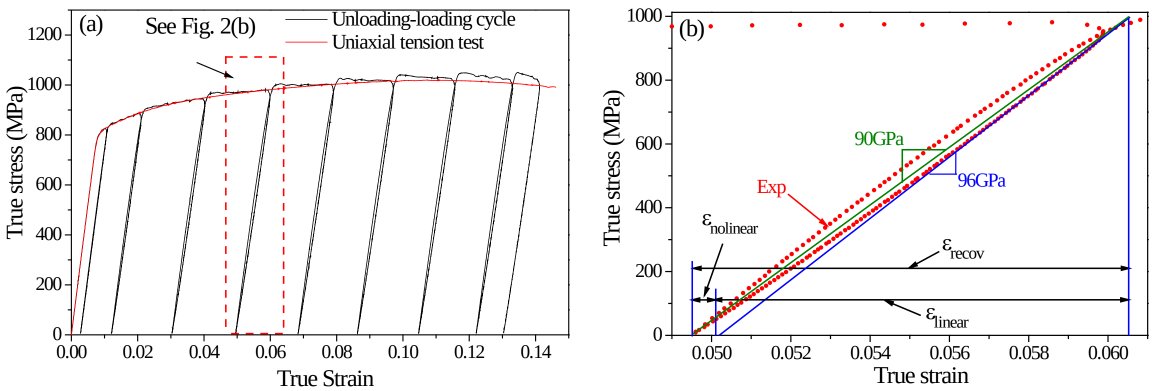

Figure 2. Stress-strain curves of HSTT under cyclic tension-unloading test

2.2. Variation of Young's modulus

Cyclic tension loading-unloading test was conducted to explore the nonlinear unloading behaviour during accommodated deformation. Figure 2 (a) illustrates The true stress-strain relationship and the Chord modulus (average Young's modulus), which are the linearly approximated stress-strain gradient

Journal of Physics: Conference Series **734** (2016) 032113 doi:10.1088/1742-6596/734/3/032113

during each unloading-reloading cycle at different pre-strains. It also can found from Figure 2 (b), the stress-strain curve of the forth cycle, that the unloading and reloading curves are not linear and the unloading curves always lag behind the subsequent loading curves, forming hysteresis loops that are more pronounced for larger plastic strain.

Figure 3 (b) shows the Chord modulus variations with accumulated plastic strain. It can be seen that the Chord modulus decreases dramatically when the plastic strain is less than 5% and turns to be a constant value when the plastic strain exceeds to 5%, and the percentage of the nonlinear recovery also turns to be stable (about 13.5%). Thus, it can be concluded that the unloading of HSTT exhibits a pronounced nonlinearity.

3. Elastoplastic constitutive modelling

3.1. Yoshida-Uemori model

Yoshida-Uemori model was used to evaluate the Bauschinger effect in Ti-3Al-2.3V tube. Y-U model is a two-surface isotropic-kinematic hardening model, wherein the yield surface moves within a bounding surface. The criterion for the subsequent yield surface *f* is expressed by the Eq. (1)

$$f = \phi(\sigma - \alpha) - Y = 0 \tag{1}$$

The bounding surface *F* is given by Eq. (2)

$$F = \phi(\sigma - \beta) - (B + R) = 0 \tag{2}$$

The Y-U model parameters (Y, C, B, b, m, R_{sat}, h) were determined simultaneously by using a FE based optimization technique. The objective function of the optimization method is defined as

$$\Gamma(x) = \sum_{t=1}^{T} \omega^t \Gamma^t(x) \tag{3}$$

where $\boldsymbol{x}$=[Y, C, B,...] is the parameters set, $\Gamma^t(x)$ is the objective function. Thus, the parameters set of the Y-U model can be optimized. It is found from Figure 3 (a) that the predicted curves well agree with the experimental results, indicating that the calibrated Y-U model are reliable.

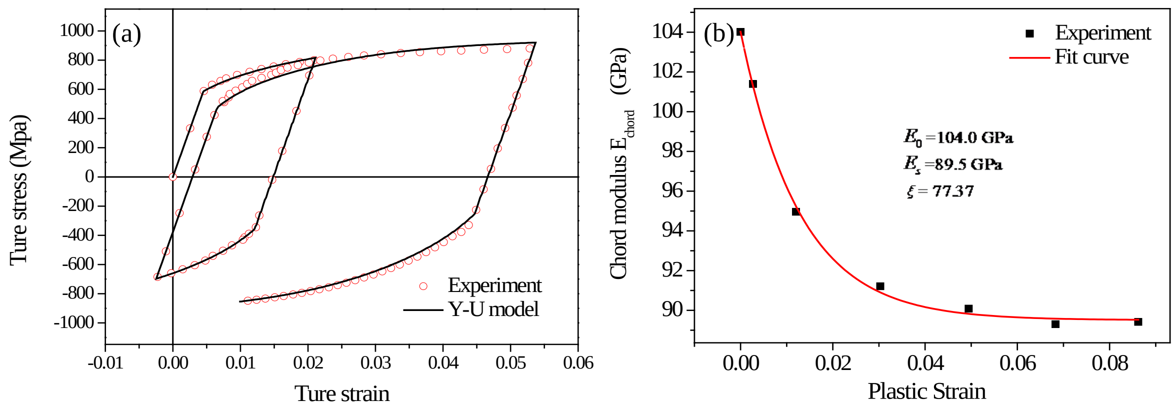

Figure 3. Comparison of experimental and calibrated results: (a) Y-U model; (b) Chord model

3.2. Chord unloading model

In order to describe the Young's modulus variation at different pre-strains, the Chord model was used in this study, as shown in Eq. (4)

$$E = E_0 - \left(E_0 - E_a\right)\left\{1 - \exp\left(-\xi\varepsilon_p\right)\right\} \tag{4}$$

where E_0 is the Young's modulus obtained by the uniaxial tension test, E_a is the converged average Young's modulus and ξ is the convergent rate. The parameters were determined by least squares method from the tension unloading-loading experimental data, as shown in Figure 3(b).

4. Springback prediction of HSTT

Taking the RDB of HSTT as a typical case, the springback was predicted and analyzed. The key modelling techniques and forming parameters can be found in Ref. [4]. The elastoplastic frame work was implemented into ABAQUS by fully implicit return mapping algorithm and stress updating algorithm. The von Mises yielding function was applied in the elastoplastic frame work. For comparison, the isotropic hardening (IH) model and constant unloading (Const. E_0) model were also used in simulation.

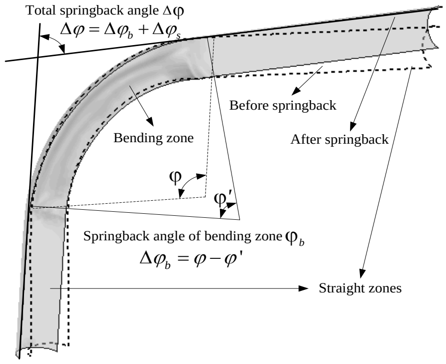

Figure 4. Schematic of springback in HSTT rotary draw bending

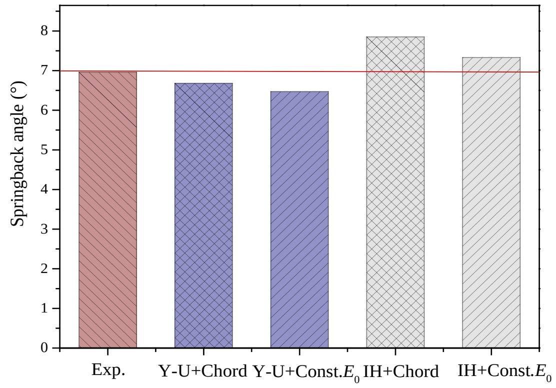

Figure 5. Comparison of springback prediction for different model combination

Figure 4 shows the schematic of springback in HSTT rotary draw bending. Figure 5 predicted springback angles under 90° bending. In comparison with IH + Chord *or* Const. E_0 models, consideration of the Bauschinger effect resulted in smaller springback angles. During tube bending and mandrel-pulling process, the reversal loading phenomenon occurs in some regions. Therefore, the stress at these areas becomes smaller when the Bauschinger effect is considered.

Compared with IH *or* Y-U +Const. E_0 models, the models considering the variation of Young's modulus gave larger springback angles due to the decrease of the Chord modulus at the bent tube. From the view of influence on springback prediction, the variation of Young's modulus seems to be more obvious than Bauschinger effect. Consequently, for accurate springback prediction, it is important to understand and consider the Bauschinger effect and variation of Young's modulus in HSTT rotary draw bending.

5. Conclusion

By using DIC-based cyclic tension-compression test and cyclic tension-unloading test, both the Bauschinger effect and variation Young's modulus were measured and clarified. To describe the two behaviours, the Y-U model and Chord model were established, calibrated and numerically implemented. Considering the Bauschinger effect and the variation of Young's modulus is of great importance for accurate springback prediction of HSTT bending.

Acknowledgements

The authors would like to thank the National Science Fund for Excellent Young Scholars (51522509), the National Natural Science Foundation of China (51275415) and Fundamental Research Funds for the Central Universities (3102014KYJD001).

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