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Springback FE modeling of titanium alloy tubes bending using various hardening models

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Abstract. In this study, effect of various material hardening models based on Holloman's isotropic, Ziegler's linear kinematic, non-linear kinematic and mixture of the isotropic and nonlinear kinematic hardening laws on springback prediction of titanium alloy (Ti-3Al-2.5V) in a tube rotary draw bending (RDB) process was investigated with presenting the keynotes for a comprehensive step by step ABAQUS simulation. Influence of mandrel on quality of the final product including springback, wall-thinning and cross-section deformation of the tube was investigated, too. Material parameters of the hardening models were obtained based on information of a uniaxial test. In particular, in the case of combined iso-nonlinear kinematic hardening the material constants were calibrated by a simple approach based on half-cycle data instead of several stabilized cycles ones. Moreover, effect of some material and geometrical parameters on springback was carried out. The results showed that using the various hardening laws separately cannot describe the material hardening behavior correctly. Therefore, it is concluded that combining the hardening laws is a good idea to have accurate springback prediction. Totally the results are useful for predicting and controlling springback and cross-section deformation in metal forming processes.

Keywords: springback; cross-section deformation; metal forming; finite element method; tube bending; ,andrel

1. Introduction

Due to some excellent characteristics such as a high specific strength, high strength to weight ratio and corrosion resistance, titanium tubes currently have been used in a wide range of applications including hydraulic pneumatic, fuel control systems in advanced aircraft and spacecraft (Boyer 1996). Among tube bending methods, rotary draw bending (RDB) is regarded as an advanced and efficient method in manufacturing bent tubes with high accuracy. In addition some problems of metal forming processes such as wrinkling and cross-section distortion, there is a problem which is named springback. Indeed, when a deformable workpiece undergoes plastic deformation during a metal forming process, final shape of the deformed workpiece is very near to configuration of forming tools. With starting unloading step and removing forming tools, final desired shape of the deformed workpiece is changed.

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This phenomenon is called springback. If this important issue is not considered in designing and manufacturing process of a part, it will create future problems especially in assembly step. Thus, springback prediction is a vital action in the metal forming process. On the other hand, springback depends on a variety of parameters and is hard to predict. For this goal, researchers consider various strategies and methods and have been trying to present an accurate prediction of springback. Some researchers have been conducting the springback prediction using analytical methods. (Wenner 1983, Al-Qureshi and Russo 2002, Yi *et al.* 2008, Li *et al.* 2012, Ján and Miroslav 2013). Due to the analytical methods are based on some simplifying assumptions, they are not usually accurate enough. Appearance of finite element method (FEM) caused a revolution in numerical works and led researchers to regard the FEM as an effective method for their studies. Numerical simulation of metal forming processes is affected by some physical parameters including hardening behavior of material, Bauschinger effect, distortional hardening, anisotropy, etc. One of main parameters is Bauschinger effect. Simply, the Bauschinger effect expresses one material which is loaded to a specific point to yield; it does not yield in the same situation when it is unloaded. In other words, the material yields in the unloading step earlier than the loading ones. Although Bauschinger effect is a necessary effective parameter in FE modeling of metal forming processes but it was not considered in most of researches (Yu and Johnson 1982, Chu 1986). Hence, researchers tried to involve the influence of Bauschinger effect in their investigations (Gau and Kinzel 2001, Alexandrov and Hwang 2011). For one thing, Gau and Kinzel (2001) proposed a new model in which the Bauschinger effect had been considered. Kadkhodayan and Zafarparandeh (2009) studied relation of bending force and final springback using a commercial FE code. Osman *et al.* suggested (2010) a semi-empirical formula for prediction of springback ratio in V-die bending process. They determined springback of sheet metals in various cases of a flanging process numerically and analytically. Kitayama and Yoshioka (2014) investigated the springback with the control of punch speed and blank holder force via sequential approximate optimization. Sathish Gandhi *et al.* (2014) conducted elastic-plastic frictionless spherical indentation analysis in order to analyze springback of the actual indentation depth after the indenter is unloaded. Due to the unique characteristics of titanium alloys, some researchers recently have focused on springback prediction of titanium alloy tubes. Sato and Ishiwata (2015) analytically investigated the bending characteristics of single- and double-walled elastic tubes contacted by an elastic material by considering the Brazier effect. Lee (2010) discussed an experimental investigation of the mechanical behavior and buckling failure of sharp-notched circular tubes subjected to cyclic bending. Li *et al.* (2012) investigated springback modeling of Ti-3Al-2.5V (TA18M) experimentally, analytically and numerically. It has to be mentioned that they considered just isotropic hardening. For instance, Li *et al.* (2012) investigated springback modeling of Ti-3Al-2.5V (TA18M) experimentally, analytically and numerically. It has to be mentioned that they considered just isotropic hardening as hardening law. Liu *et al.* (2012) with considering strength-differential effect in FE modeling tried to improve accuracy of thick-walled titanium alloy tube in RDB. Jiang *et al.* (2010) investigated effects of the bending angle and the material properties on the springback angle of titanium alloy tubes during numerically controlled bending. Zhiqiang *et al.* (2011) as well as Heng *et al.* (2007) investigated changes of geometrical characteristics and stress distribution of tube in RDB experimentally, analytically and numerically. These all indicate springback depends on variety of parameters. Therefore, in present article, influences of various hardening models on springback simulation of titanium alloy tubes (Ti-3Al-2.5V) was studied using FE modeling. Then improvement of accuracy of this prediction by combining these hardening models was investigated. Unlike the most studies which obtain material parameters of

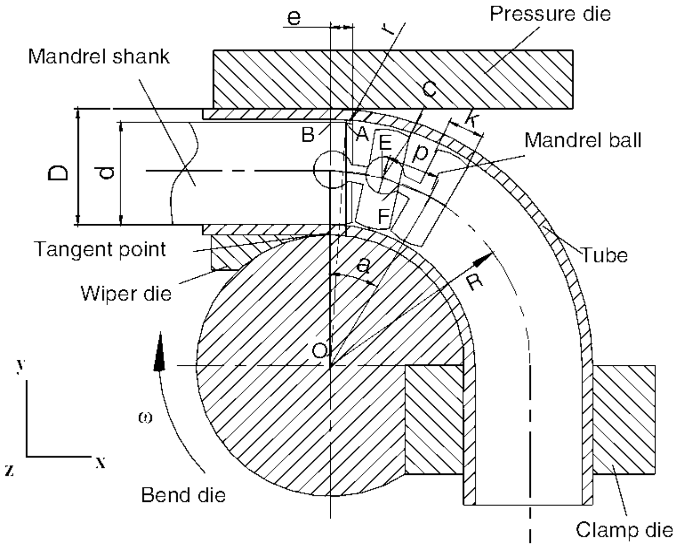

Fig. 1 Schematic of RDB (Heng *et al.* 2007)

nonlinear kinematic hardening and combined iso-nonlinear kinematic hardening in particular by information of several stabilized cycles curve, in this study, material constants of the combined iso-nonlinear kinematic hardening laws were calibrated using a simple strategy based on information of half-cycle data. Our study is restricted to the effect of hardening laws on springback prediction but there are varieties of geometrical, numerical and material parameters which effect on the springback modeling. One of the most effective parameters is elasticity modulus which is changed during plastic deformation. In the general theory of plasticity, material unloading behavior is assumed linear with a slope equal the elasticity modulus whereas experimental results indicate elastic behavior in unloading is not linear and has a little curvature and it depends on the plastic strain (Cleveland and Ghosh 2007, Yoshida and Uemori 2002). Chatti and Hermi (2011), Chatti and Fathallah (2012), and Vrh *et al.* (2011) considered changes of the elasticity modulus during plastic deformation in springback prediction which resulted in improving results. Recently, Shahabi and Nayebi (2015) studied influence of the continuum damage on springback prediction in metal forming based on Lemaitre's isotropic unified damage law. These all show that springback is a very sensitive phenomenon. Hence, it is hard to predict it and influences of other parameters should be studied by other researchers to have acceptable design. Thus, the effect of various describing material hardening behavior on springback prediction of titanium alloy (Ti-3Al-2.5V) in a tube rotary draw bending (RDB) process was investigated in this study by FE modeling.

2. Comprehensive FE simulation of RDB

Since there is rarely a comprehensive consideration for FE simulation of RDB process, here, it has tried to express a somedeal presentation of 3-D FE simulation of the RDB processes using FEM. Other FE considerations of RDB process simulation can be found in study of Zhao *et al.* (2009).

Table 1 Forming parameters used in experimental and numerical study (Li *et al.* 2012)

Item	Value
Bending radius, R [mm]	3×D
Relative pushing speed, V_p/V	1
Bending angle [˚]	101.3
Mandrel diameter, d [mm]	8.35
Mandrel extension length, e [mm]	0
Number of balls	1
Thickness of balls [mm]	3.5
Pitch of balls [mm]	2
Ball diameter [mm]	8.32
Length of mandrel shank [mm]	120
Length of clamp die [mm]	28.6
Length of pressure die [mm]	132.7
Length of wiper die [mm]	300

2.1 Geometry modeling

RDB process is composed of a tube and several dies including bending die, clamp die, wiper die and pressure die that the tube is placed between the bending dies during doing of process (Fig. 1).

Tube was defined as a solid deformable part whereas all the dies, the mandrel and balls were treated as discrete rigid bodies. For saving in running time a half model of RDB process was presented. Here, a tube with geometrical specification (D×t) ∅9.53 mm×0.51 mm and length of 100 mm was considered for simulating the RDB process. Other geometrical forming parameters are illustrated in Table 1. All forming information was extracted from work of Li *et al.* (2012).

2.2 Material properties definition

The elasticity modulus of E=104.9 (GPa) and Poisson ratio of υ=0.39 were used to describe tube's mechanical properties and ρ=4470 (kg/m^3) was considered as tube's density (Liu *et al.* 2012). Tube material was assumed isotropic, homogenous. Moreover, strain rate and temperature effects were neglected. It is important to notice that in large deformation case, true stress-strain curve of material (not engineering ones) must be utilized for describing material hardening behavior during plastic deformation.

2.3 Assembly and solving FE equations

All created parts in previous modulus were inserted in Assembly modulus as dependent instances. A dynamic/explicit solver was used for solving FE equations. Because of dealing with large deformations in RDB, "Nlgeom" point was selected as "On" case in order to the nonlinear effects are considered. According to the work of Li *et al.* (2012), the mass scaling of 5000 was considered as optimum value for this study. It has to be mentioned that as a general law, ratio of kinematic energy to total ones must not exceed approximately 0.05.

Table 2 Friction conditions in various contact interfaces (Li *et al.* 2012)

Contact interfaces	Coefficient of friction
Tube wiper die	0.1
Tube-pressure die	0.3
Tube-clamp die	Rough
Tube-bend die	0.25
Tube-mandrel	0.05
Tube-flexible balls	0.1

2.4 Contact description

In RDB process seven contact pairs exist that must be defined which are the contact between tube outer surface and clamp die surface, tube outer surface and bend die, outer surface of tube and pressure die, outer surface of tube and wiper die, inner surface of tube and mandrel, inner surface of tube and balls, mandrel and balls. The “Surface to surface” contact model was utilized for the all contact pairs. A “Kinematic contact method” was considered as mechanical constraint formulation for all contact pairs except for the contact among tube-mandrel, tube-ball and mandrel-balls “Penalty contact method” was employed. The classical Coulomb frictions model as well as a penalty function approach was used to present friction behavior. Relative movement between mandrel and ball is so complex. Hence, contact between mandrel and balls as well as among ball and ball was defined using a “link+rotation” connector element.

2.5 Loading and boundary conditions

All boundary conditions (BC) were applied using two modes of displacement/rotation and velocity/angular velocity. The clamp die and bend die have the same degree of freedom and are rotate together around the bend center with the same angular velocity. A smooth step was selected in order to define smooth loading of all the tools to reduce inertial effects in explicit simulation of the quasi-static process. The wiper die and mandrel are fixed during doing the RDB process. The pressures die moves at the same linear speed with the bend die and clamp ones. The balls also depending on bending operation have a limited rotation around the bend center. “ZSYMM”BC was used to meet the requirement of symmetry for the half-modeled tube.

2.6 Meshing

Generally, a solid (3-D) element is employed when ratio of outside diameter to thickness (D/t) is less than 15; otherwise shell element is utilized (Feifei *et al.* 2013). The ratio of investigated high strength titanium tube (HSTT) is 18.7. Because it is close to critical value of 15, thus it must be investigated. Investigation of Feifei *et al.* (2013) indicated solid (3D) elements are more suitable for springback prediction rather than shell ones. Because an explicit solver was utilized for solving FE equations, the explicit was picked from element library section. Quadratic reduced-integration elements are generally the best choice for most general stress/displacement simulations, except in large-displacement simulations involving very large strains and in some types of contact analyses. Thus, C3D8R elements which are 8-node linear brick, reduced integration elements with hourglass control were used in order to mesh the tube by considering with four elements through the thickness. All rigid parts were meshed by discrete rigid elements of R3D4 which are 4-node 3-D bilinear rigid quadrilateral elements.

2.7 Springback modeling

A general static step was generated with considering nonlinearity effects. “Specify damping factor” was considered as automatic stabilization. Feifei *et al.* (2013) also concluded that considering this kind of stabilization results in better springback prediction. Their investigation also indicated that the initial increment size does not have a significant influence on simulation results. In the predefined field container, “Initial” was picked as step, “Other” as category, and “Initial State” as type. A new job was created and submitted.

2.8 Hardening laws

In this study, four hardening models of isotropic (IH), linear kinematic (LKH), nonlinear kinematic (NLKH) and combined IH+NLKH hardening models were used to describe the material hardening behavior. In isotropic hardening case, the following Holloman’s law was considered in which “ε_p” is plastic strain, “K” hardening coefficient and “n” hardening exponent.

$$\sigma = k\varepsilon_p{}^n \tag{1}$$

The Ziegler model was utilized to describe the linear hardening behavior. The evolution of linear hardening model consist of a linear translation of the yield surface through the backstress, “x”. When temperature dependence is omitted, this evolution law is the following linear Ziegler hardening model

$$\dot{x} = C\frac{1}{\sigma_0}(\sigma - x)\dot{\varepsilon}_p \tag{2}$$

in which “x” is backstress, “C” kinematic hardening modulus and “σ_0” initial size of yield surface. Since this simple model can predict only linear hardening, the test data obtained from a half cycle of unidirectional tension or compression must be linearized. ABAQUS expect users to provide only two data pairs to define this linear behavior: the yield stress at zero plastic strain ($\sigma|_0$) and yield stress (σ) at a finite plastic strain value (ε_p). Hence, the linear kinematic hardening modulus (C) is determined from the relation (3)

$$C = \frac{\sigma - \sigma|_0}{\varepsilon_p} \tag{3}$$

The nonlinear kinematic hardening model is an additive combination of a purely kinematic term (the linear Ziegler hardening law) and a relaxation term which so-called is named recall term that introduces the nonlinearity. This model is

$$\dot{x} = C_k\frac{1}{\sigma_0}(\sigma - x)\dot{\varepsilon}_p - \gamma_k x\dot{\varepsilon}_p \tag{4}$$

Table 3 Hardening coefficients

K (MPa) (Li *et al.* 2012)	n (Li *et al.* 2012)	C (MPa)	C_k (MPa)	γ_k
1239.55	0.0914	1534.5	3156.5	10.13

Fig. 2 Springback prediction based on various hardening laws

Integrating of relation (3) over a half cycle, yields Eq. (5)

$$x = \frac{C_k}{\gamma_k}(1 - \exp(-\gamma_k \varepsilon_p)) \tag{5}$$

"C_k" and "γ_k" are material parameters that must be calibrated from stabilized cyclic test data. Since producing the stabilized cyclic stress-strain curve is more difficult than simple uniaxial ones and as well as most of times a user may only have data from a single tension test, there is a noticeable interesting in using information of the simple uniaxial test as half cycle data instead of tension-compression ones. Hence, a user can calibrates material constants of the nonlinear kinematic hardening model as bellow. Because there is no cyclic test data to correlate the material parameters, this method may be adequate only when dealing with a few cycles. In order to calibrate the hardening coefficients (C_k and γ_k) of combined iso-kinematic hardening model steps bellow must be followed: subtract the yield stress (σ_y) from stress data of simple uniaxial tensile test which leads to get the backstress ($x=\sigma-\sigma_y$). This way one will be able to obtain backstress-strain curve based on the stress-strain curve data. Now, Eq. (5) must be fitted to the backstress-strain curve so that you can get the hardening coefficients C_k and γ_k. Although there are various strategies and opportunity to curve fitting but it can be carried out simply by Microsoft Excel's solver Add-In, as a suggestion. For more information and examples see (Lemaitre and Chaboche 1990, Imaoka 2008). Finally, the hardening constants were obtained as Table 3.

3. Results and discussion

With considering all aforesaid notes, FE modeling of the RDB process was carried out and the results were obtained such bellow. Fig. 2 illustrates capability of the various hardening models for springback prediction. It can be obtained that combining the hardening laws leads to improve the

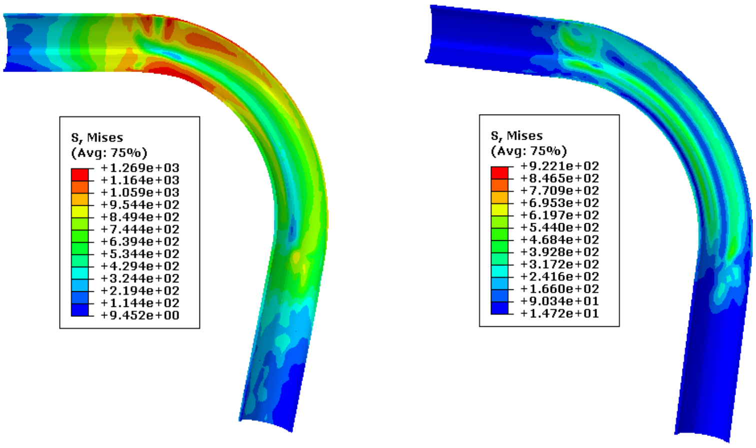

Fig. 3 Von Mises Stress distribution of HSTT (left: bending, right: springback)

springback prediction. In the other word, using the hardening laws separately cannot describe the material hardening behavior correctly. In general, isotropic hardening expresses that occurring plastic deformation results in uniform expanding the yield surface in all directions. Instead, kinematic hardening states the yield surface is translated in the stress space without any expansion. Whereas in real case, the yield surface can be expanded and translated simultaneous. Therefore, considering the hardening laws separately doesn't lead to describe correctly the material hardening behavior. Thus, combining the hardening models can be considered as a good idea in order to have a more accurate modeling and improve springback prediction.

As another example, Fig. 3 shows the von Mises stress distribution within the bent HSTT at end of loading step and springback ones. Since springback is related to release a part of elastic strain, after occurring springback, stress level decreases in the bent tube.

Tube bending process leads to cross-section deformation and wall thinning of tube that are considered as effective factors on the tube quality. Hence, capability of the various hardening models in prediction of cross-section deformation and wall thinning of the HSTT was investigated, too. Fig. 4 and Fig. 5 illustrate results of this investigation in angles of 30°, 60° and 90° from initial bending section to bending tangent. Wall thinning degree (Δt) and cross-section deformation (ΔD) are expressed as

$$\Delta t = \left| \frac{t - t'}{t} \right| \times 100\% \tag{6}$$

$$\Delta D = \frac{D - D'}{D} \times 100\% \tag{7}$$

Where "t" is tube initial wall thickness, "t'" the minimum wall thickness after bending, "D" the initial tube outside diameter, "D'" the section length in the vertical direction after bending.

One can found from the Fig. 4 and Fig. 5 that combination of the hardening models furthermore improving the springback prediction, results in improving predicting the cross-section deformation and wall thinning, too. One of the most effective tools on quality of the bent tubes is mandrel. Generally, the mandrel is composed of mandrel shank and ball. The balls number can be changed

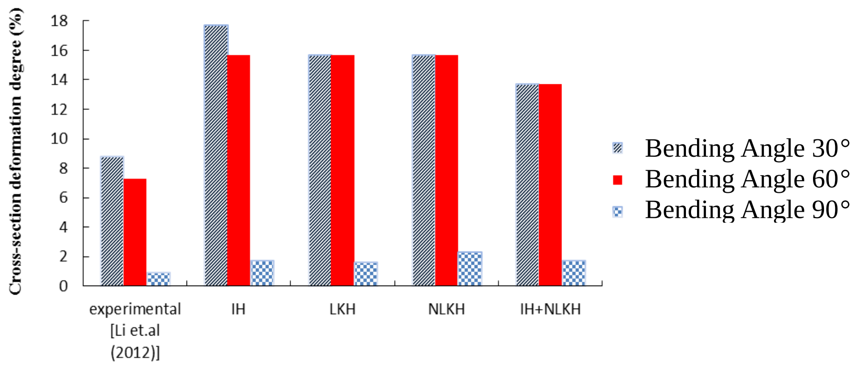

Fig. 4 Cross-section deformation of the HSTT

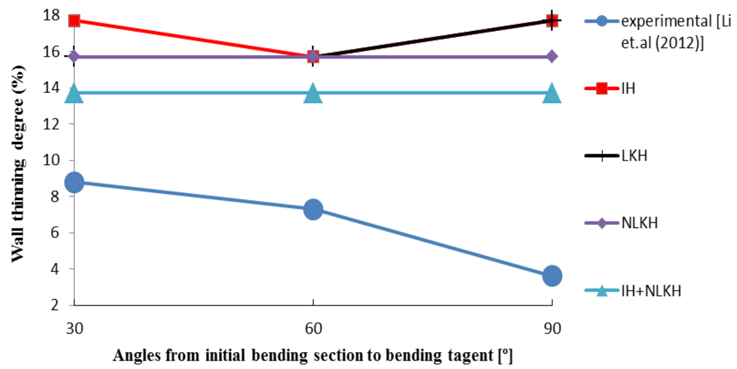

Fig. 5 Wall thinning degree of the HSTT

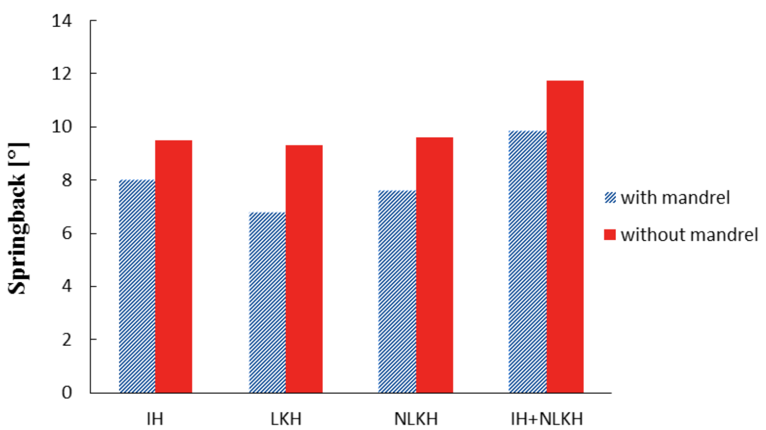

Fig. 6 Influence of mandrel on springback of the HSTT

from zero to several. Here, influence of the mandrel on some quality effective factors of the bent tube was investigated. A more comprehensive investigation on mandrel role on stress distribution can be found in study of Heng *et al*. (2007). Fig. 6 depicts influence of mandrel on amount of HSTT springback. The results of this investigation showed that neglecting the mandrel in tube bending process results in increasing the springback.

As another example, Fig. 7 and Fig. 8 illustrate the influences of the mandrel on cross-section degree and wall thinning of the HSTT, respectively. It has to be mentioned that combining IH and NLKH (IH+NLKH) are considered as hardening behavior describing model.

Fig. 8 indicates that the mandrel has a significant effect on quality of the bent tube. Indeed, mandrel with applying an internal pressure on tube inside wall avoid cross-section changing significantly. In addition, Fig. 8 illustrates that the mandrel leads to increase wall thinning degree of the HSTT. In the other word, when the tube moves to turn around the bend die, friction between tube and mandrel results in more wall thinning rather than without mandrel case. Fig. 9 illustrates due to mandrel avoid more cross-section deformation, thus less bending moment need for accomplishing the RDB process.

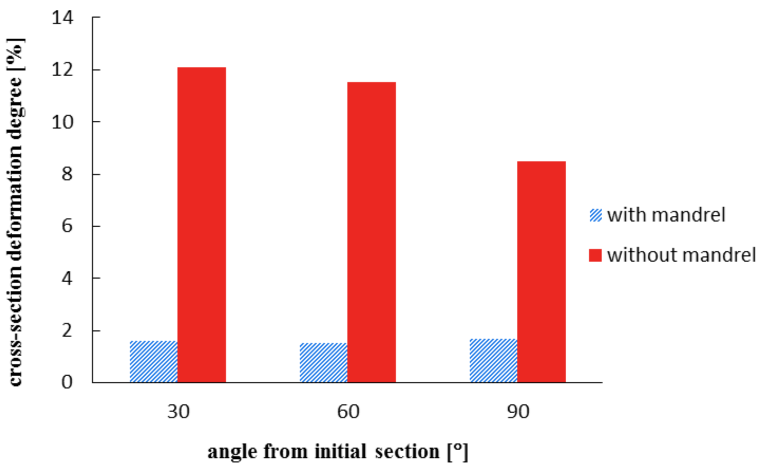

Fig. 7 Influence of mandrel on cross-section deformation of the HSTT

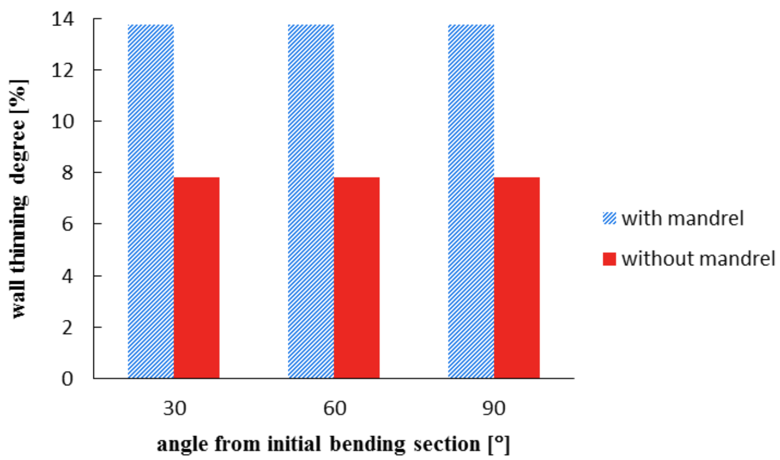

Fig. 8 Influence of mandrel on wall thinning of the HSTT

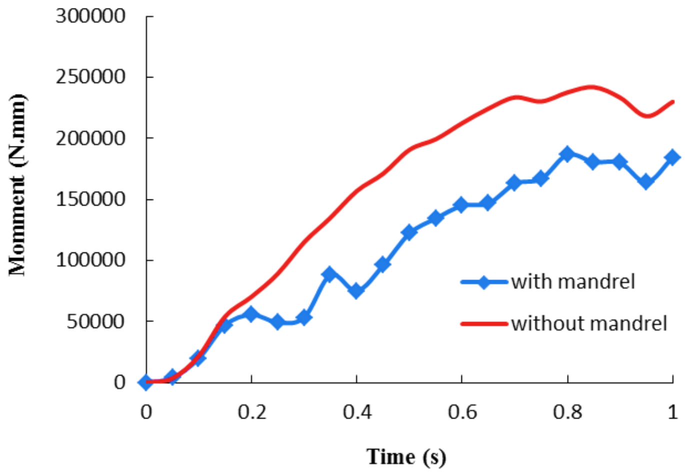

Fig. 9 Influence of mandrel on required bending moment of HSTT

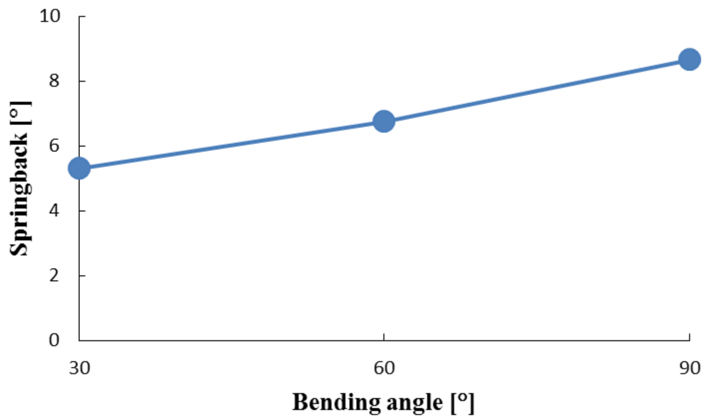

Fig. 10 Influence of bending angle on springback

In following, dependency of springback on various material and geometrical parameters is investigated. For all these examples, IH+NLKH case considered as hardening describing model. Fig. 10 shows dependency of the springback on bending angle. According to this figure one can easily find that increasing the bending angle will cause the springback to increase. This conclusion is compatible with other researcher's analytical formulas.

As another example, Fig. 11 illustrates the effect of the elasticity modulus on springback. It indicates that materials with less elasticity modulus have more springback. In the other word, more ductile materials (e.g., Aluminum) have more springback in comparison with stiff ones (e.g., high strength steels).

The hardening coefficient (K) and hardening exponent (n) play an important role as material effective parameters. Figs. 12-14 depict the effects of these parameters on the results. According to Fig. 12, it is observed that increasing the hardening coefficient result in increasing the springback. In Fig. 13, the stress-strain curves of two materials with different hardening coefficients ($K1<K2$) are considered. From this figure, it is observed that the material with lower hardening coefficient

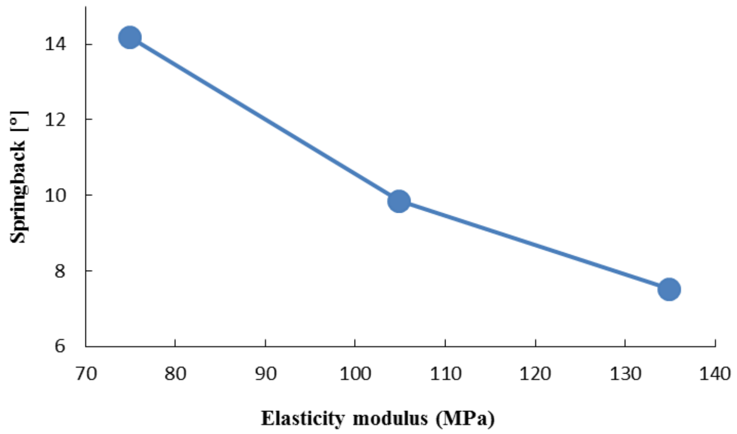

Fig. 11 Influence of elasticity modulus on springback

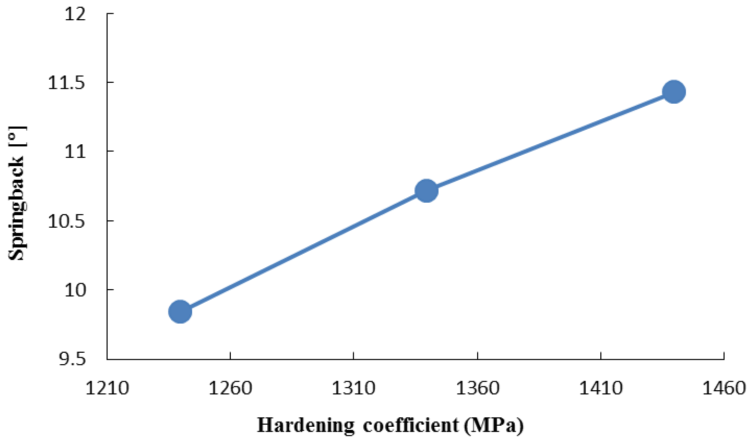

Fig. 12 Influence of hardening coefficient (*K*) on springback

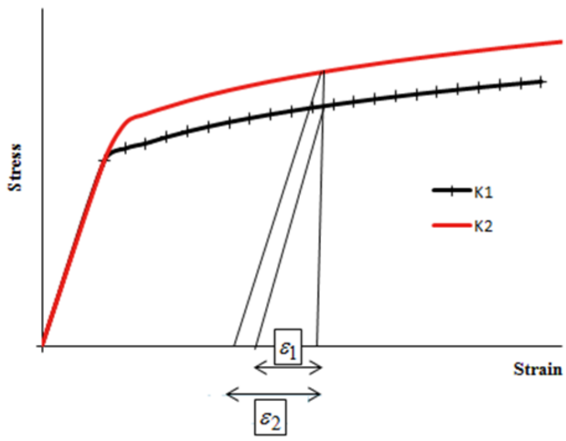

Fig. 13 Stress-strain curve for different hardening coefficients

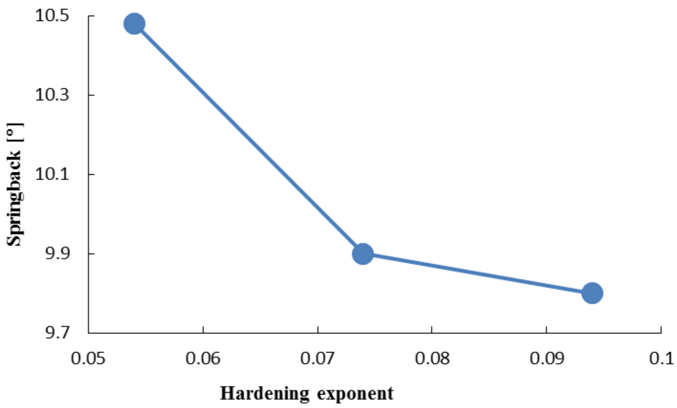

Fig. 14 Influence of hardening exponent (n) on springback

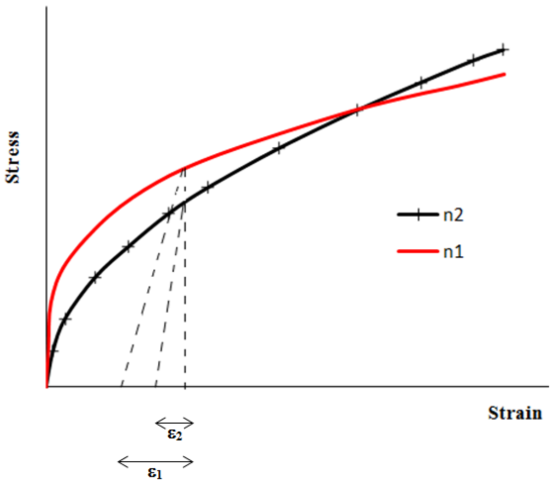

Fig. 15 Stress-strain curve for different hardening exponents

has lower springback. Same justification is true for the hardening exponent (n) according to Figs. 14 and 15 (Jiang *et al.* 2010).

4. Conclusions

In this study, capability of the various hardening models for springback prediction of tube was investigated. Influence of mandrel on quality of bent tube was investigated, too. The results showed that using the hardening models separately cannot describe material hardening behavior correctly. Therefore, combining the hardening models is a good idea in order to improve accuracy of springback prediction. As another conclusion, mandrel lead to more walls thinning of the tube but have a significant and positive influence on decrease of springback, cross-section deformation and required bending moment for accomplishing the RDB process. Thus, it was found that mandrel is a vital tool in tube bending process which should be considered. Parameter study also indicated that springback depends on variety of factors and that's why it is hard to predict. Therefore, to have a more accurate springback prediction, several factors must be considered simultaneously.

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