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Liqun Niu

Xi'an Jiaotong University

Qi Zhang (✉ henryzhang@mail.xjtu.edu.cn)

Xi'an Jiaotong University

Bin Han

Xi'an Jiaotong University

Research Article

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Posted Date: August 19th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-818932/v1>

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Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on January 23rd, 2022. See the published version at <https://doi.org/10.1007/s00170-021-08527-9>.

Material characteristics evaluation for DC04-welded tube hydroforming

Liqun Niu, Qi Zhang *, Bin Han

School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China

henryzhang@mail.xjtu.edu.cn; Tel: +86 18629087688; Fax: +86 029 82668607

*Corresponding author: Qi Zhang

Abstract

Tube hydroforming (THF) technology is widely applied, especially in the automotive and aircraft industries. Material characteristics of tubular workpieces should be evaluated in terms of bending and THF processes. A mathematical model, which combines the assumption of elliptical contour of a bulged wall and the prediction equation of wall thickness, is provided to analyze the THF process and to obtain the strain-stress relationship of tubes. Material characteristics of a DC04-welded tube is obtained by using a self-designed THF test machine. Considering the effects of pre-work hardening, we discuss the material strain-stress relationships of the tube and original sheet blank. An approximate determination method is proposed to obtain the stress-strain curve of the tube by using the curve of the original sheet blank and the hardness of the tube and sheet blank. A suitable constitutive equation with pre-work hardening is applied to the DC04-welded tubes through simulation and experimental methods.

Keywords: Material characteristics; Welded tube; Sheet blank; Finite element simulation

Introduction

Nomenclature

L	length of the bulging region	σ_{φ}	stress in meridian direction
r	initial radius of the tube	σ_{θ}	stress in circumferential direction

t_0	initial wall thickness	σ_t	stress in normal direction
t_b	thickness of the point b	$\bar{\sigma}$	equivalent stress
h_i	bulging height	ε_φ	strains in meridian direction
R_a	radius of the elliptic contour in the x-axis	ε_θ	strains in circumferential direction
R_b	radius of the elliptic contour in the y-axis	$T(x_b, y_i)$	tangent point coordinates of the bulging region contour and mold contour
R_r	radius of the die	ε_t	strains in normal direction,
P_i	internal bulging pressure	$\bar{\varepsilon}$	equivalent strain
ρ_φ	meridian radius of curvature	ρ_θ	circumferential radius of curvature
σ_{ST}	yield strength of the tube	H_T	Vickers hardness of the tube
σ_{SB}	yield strength of the sheet blank	H_B	Vickers hardness of the sheet blank

Tube hydroforming (THF) technology is widely applied, especially in the automotive and aircraft industries [1, 2]. The technology is based on the plastic deformation of welded tube using a pressurized fluid [3]. Compared with traditional stamping, THF provides the following advantages: low costs, improved strength and stiffness, uniform wall thickness distribution, and few secondary operations [4, 5]. Material characteristics (flow stress, yield strength, and ductility) are of critical importance for reliable finite element (FE) simulations of THF [6]. It is now realized that tube bulging test provides better data than sheet tensile test for THF simulation [7]. However, the lack of availability of measurement hardware often overshadows the advantages of tube bulging test. Therefore, looking into the relationship of material characteristics between the original sheet blank and tube and proposing an approximate determination method to obtain the stress-strain curve of the tube is of critical importance in industry.

So far, tube bulging test methods have been studied by many researchers. Sokolowski et al.

[8] designed a tube bulging device to apply axial loads on the tube. Tube material properties were examined by using hydraulic bulge testing method. Strano and Altan [9] described the superiority of obtaining the strain-stress curve through a hydraulic bulging test and proposed an inverse energy approach to determine the flow stress of tubular materials. Velasco and Boudeau [10] performed an in-depth study on an analytical model to obtain material characteristics with tube bulging tests but committed an error evaluation through differential analysis by using the analytical model. They found that thickness strongly influences the stress evaluation. In the early stages of research, the contour of the bulging area is assumed circular before a novel assumption of the contour shape is presented. Hwang and Lin [11] developed a mathematical model to determine the flow stress of isotropic tubular materials under the new assumption that the profile of the bulged region is an elliptical contour. They found that the elliptical model is more efficient than the circular model [12]. Ourane et al. [13] presented a semi-analytical model and revealed the influence of the initial wall thickness t_0 on the accuracy of the hardening curve. Muammer et al. [14] described an on-line and continuous measurement of flow stress for tubular materials and obtained results that match well with off-line measurements. Analytical models for thickness prediction are consistent with experimental measurements. Yuan et al. [15] evaluated the formability of an aluminum alloy friction stir-welded tube by examining the relationship of microstructures with plastic deformation and the hydraulic bulging process through simulations. They found that the welded nugget unlikely dominates failure during hydraulic bulge test, and the tube exhibits high formability. Khalfallah [16] proposed a simplified method to obtain the characteristics of welded tubes by considering the welding bead and heat-affected zone. This method is assessed by comparing simulation predictions with experimental measurements. Zribi et

al. [17] also proposed an inverse approach strategy that comprises an optimization algorithm combining the results of experimental free-bulging test and simulation to determine the constitutive parameters of tubular materials. They also observed that the predicted parameters are consistent with experimental data. He et al. [18] established a practical technique to characterize the deformation behavior of tubular materials and demonstrated that the three key factors controlling the accuracy of equivalent stress-strain curve obtained by hydro-bulging tests are reasonable analytical models of stress and strain components, precise description of the profile in the bulging zone, and accurate data of pole thickness. Recently, Suttner and Merklein [19] presented a strain rate controlled hydraulic bulge test using the Digital Image Correlation (DIC). But the closed dies are not adapted for measures with DIC systems [7]. Khalfallah et al. [20] proposed a reverse identification approach, which minimizes the error between experiment and FE simulation of the tube bulging. This approach is effectual but the time cost is expensive.

Although great progress on tube bulging test methods has been made, there still lacks applicable and simple approach to obtain the stress-strain curve of tube. Tubes are produced by multiple roll bending and then welded, as shown in Fig. 1. Material characteristics of welded tube and sheet blank are different that may due to multiple roll bending. Therefore, the effects of plastic deformation in initial roll bending on the material characteristics of welded tubes should be considered. Meanwhile, the effects of anisotropy coefficients of sheet blanks on THF should also be investigated.

Fig. 1 Diagram of roll bending process

In this study, a mathematical analytical model was used, and the assumption of an elliptical bulge contour [12] and the prediction equation of wall thickness [14] was combined. The hydro-bulging tests on the DC04-welded tubes were conducted and the strain–stress curves of the tube were obtained by using the self-designed equipment TUBEHYDRO-1. The analytical model was verified by comparing the results from FE simulation and experimental data. An approximate parameter determination was proposed to define the material characteristics of the tubes from the original sheet blanks.

1. Mathematical analysis model

The model of the free-bulging process for thin tubes is shown in Fig. 2. The two ends of the tube are fixed by the die and hence retain the length of the free-bulge region L in a constant value. The axial section profile of the free bulge region is assumed to be an elliptical curve.

Fig. 2 Free bulging process model

The contour equations can be presented on the basis of the geometrical relationship and tangent point coordinates $T(x_i, y_i)$ [12]:

$$\frac{x_i^2}{R_a^2} + \frac{y_i^2}{R_b^2} = 1 \quad (1)$$

$$\left(x + \frac{L}{2}\right)^2 + (y - r - R_r)^2 = R_r^2 \quad (2)$$

The following equation can be obtained on the basis of the geometric constraints of the tangent point T :

$$\frac{dy_i}{dx_i} = -R_b \frac{x_i}{R_a^2} \left(1 - \frac{x_i^2}{R_a^2}\right) = \frac{x_i + L/2}{R_a + R_b - y_i} \quad (3)$$

$$R_a = \left(x_i^2 - x_i y_i \frac{r + R_r - y_i}{x_i + L/2}\right)^{1/2} \quad (4)$$

$$R_b = \left(y_i^2 - x_i y_i \frac{x_i + L/2}{r + R_r - y_i}\right)^{1/2} \quad (5)$$

In addition, the radius of the elliptic contour in y axis R_b can be expressed as

$$R_b = r + h_i \quad (6)$$

The bulging height, h_i , can be obtained in real-time measurement during the bulging test; thus, R_b can be easily obtained through Eq. (6). Once R_b is known, the coordinates $T(x_i, y_i)$ can be obtained from Eqs. (1)–(5), and R_a can be determined with Eq. (4).

During the tube bulging process, the stress state of the highest point b is shown in Fig.3.

The circumferential and meridian radii of curvature ρ_θ and ρ_φ at point b can be obtained, respectively:

$$\rho_\theta = R_b \quad (7)$$

$$\rho_\varphi = R_a^2 / R_b \quad (8)$$

From the force equilibrium at point b , we can obtain

$$\frac{\sigma_\varphi}{\rho_\varphi} + \frac{\sigma_\theta}{\rho_\theta} = \frac{P_i}{t_b} \quad (9)$$

$$\sigma_\varphi = \frac{P_i(\rho_\theta - t_b)^2}{2t_b(\rho_\theta - t_b/2)} \quad (10)$$

$$\sigma_\theta = \frac{P_i(\rho_\theta - t_b)}{2t_b(\rho_\varphi - t_b/2)}(2\rho_\varphi - \rho_\theta - t_b) \quad (11)$$

In addition, at point b, the stress along normal direction is

$$\sigma_t = P_i \quad (12)$$

Therefore, the equivalent stress can be expressed as follows:

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_\varphi - \sigma_\theta)^2 + (\sigma_\varphi - \sigma_t)^2 + (\sigma_t - \sigma_\theta)^2} \quad (13)$$

The strains can be determined on the basis of the assumption of volume invariance:

$$\varepsilon_\theta + \varepsilon_\varphi + \varepsilon_t = 0 \quad (14)$$

where the strains in circumferential and normal directions, ε_θ and ε_t , respectively, can be obtained as [14]:

$$\varepsilon_\theta = \ln \left(\frac{R_b - t_b/2}{r - t_0/2} \right) \quad (15)$$

$$\varepsilon_t = \ln \left(\frac{t_b}{t_0} \right) = - \frac{\ln(\rho_\theta/r) \times (3/2 - \rho_\theta/2\rho_\varphi)}{3/2 - \rho_\theta/\rho_\varphi} \quad (16)$$

The relationship of the thickness of point b t_b and the initial wall thickness t_0 could be expressed as follows:

$$t_b = e^\alpha t_0 \quad (17)$$

where the nondimensional α parameter is defined as:

$$\alpha = - \frac{\ln(\rho_\theta/r) \times (3/2 - \rho_\theta/2\rho_\varphi)}{3/2 - \rho_\theta/\rho_\varphi} \quad (18)$$

Once the strains in circumferential and normal directions are calculated, the equivalent strain

can be determined as:

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}} \sqrt{\varepsilon_\theta^2 + \varepsilon_\theta \varepsilon_t + \varepsilon_t^2} \quad (19)$$

Fig. 3 Stress state of the highest point b

2. Test method and experimental set-up

The experimental set-up includes the main mechanical body, the high-pressure liquid system, and the hydraulic system that provide the sealing force. As shown in Fig. 4(a), the main mechanical structure for the bulging test includes dies, left and right movable plates, upper and lower baffle plates, left and right punches, and a shutoff valve. The highest pressure the set-up can sustain is 230 MPa, and the highest sealing force is 600 kN. The laser displacement sensor was used to measure the bulging height of point *b*. As shown in Fig. 4(a)–(d), the specific testing process was as follows:

(a) The dies were first placed into the two left and right movable plates before the tube was placed in the die cavity.

(b) The length of the bulging region was determined by the geometric dimensions of the

baffle plates. The flaring and sealing of the tube were exerted by the cone-shaped punches.

(c) The high-pressure liquid was injected into the tube via the channel of the right punch.

(d) As soon as the shutoff valve was closed, the high-pressure liquid was injected into the tube to implement the bulging test.

(a) Experimental set-up

(b) Flaring and sealing process

(c) Injection process

(d) Bulging process

Fig. 4 Diagram of testing principle

During the bulging test, the bulged height was measured in real-time by the laser displacement sensor. The bulged pressure inside the tube is acquired by the pressure transducer. The dies in the active plates can be easily replaced to meet the requirements of different tube diameters.

In the present study, DC04-welded tubes were tested. The geometries parameters of the tubes are shown in Table 1. The bulge test equipment is shown in Fig. 5, and it can be employed to test for the tubes of different sizes.

Table 1. Geometric parameters of the tube

Material	Diameter of the tub (mm)	Thickness (mm)	Length of the bulging region (mm)
DC04	65	1.7	130

(a) Bulging test equipment

(b) Inner experimental set-up

Fig. 5 Bulging test equipment TUBEHYRO-1

3. Material property test

3.1 Tensile test of original sheet blank

The tensile tests of the sheet blanks were conducted by the INSTRON 5982 material test machine. The sheet blank was the raw material of the DC04-welded tube. The test samples were cut from the sheet blank according to the Chinese national standard GB/T 228-2008, as shown in Fig. 6.

Fig. 6 True strain–stress curve of the sheet blank for rolling direction

The true strain-stress curve of the sheet blank for rolling direction was obtained by a tensile test, as shown in Fig. 6. The least square method was used to fit the strain-stress curve. The objective function was $\sigma = K\varepsilon^n$, and the fitting results calculated the strength coefficient $K = 564.4\text{MPa}$ and the hardening exponent $n = 0.29$.

According to the angles 0° , 45° , and 90° from the rolling direction of the sheet blank, three types of tensile test samples were prepared. The Lankford coefficients at the engineering strain of 15% were obtained by the uniaxial tensile test at room temperature, as shown in Table 2.

Table 2. Lankford coefficients of the sheet blank

Material	r_0	r_{45}	r_{90}	$\bar{r}$
DC04 (sheet)	2.51	1.89	2.94	2.45

3.2 Hardness test of tubes and sheet blanks

The DC04-welded tubes were made from the sheet blanks through bending and welding processes. The hardness tests were conducted to identify that whether the material characteristics of tubes are affected by the forming process. From the forming process, the deformation of the tube was symmetrically distributed, as shown in Fig. 7. Namely, each section of the tube, from A to H, was symmetric along the vertical symmetric axis. In addition, the section A (0°) is the weld joint. Thus, only sections A to E are discussed.

Fig. 7 Sections of the tube

With the digital micro-hardness tester, the Vickers hardness of the five sections of the tube

from A to E were measured five times along the thickness direction. The Vickers hardness of the sheet blank was also measured. The average hardness values are shown in Table 3. Obviously, the average Vickers hardness of the section A was the highest, whereas the average Vickers hardness of the section E was the lowest. The average Vickers hardness of the sheet blank was lower than all the five sections of the tube because non-uniform plastic deformation occurs in the tube during the roll bending process.

Table 3. Average Vickers hardness

Test objects	Tube					Sheet blank
	A	B	C	D	E	
HV (kgf/mm ²)	115.3	107.4	103.8	105.4	99.5	83.3

3.3 Bulging test of tube

Bulging tests of the DC04-welded tubes were performed with the bulging test equipment TUBEHYRO-1. The bulging height–pressure curves of the five sections A–E were collected. The data of the five sections were compared after filtering, as shown in Fig. 8. From Fig. 8(b), which is an enlarged view of the A zone in Fig. 8(a), the deformation behaviors of these sections are obviously different from each other in the elastic deformation stage. In the later stage of plastic deformation, as shown in Fig. 8(c), the deformation behaviors are almost identical.

(a) Bulging height-pressure curves

(b) Enlarged view of the A zone

(c) Enlarged view of the B zone

Fig. 8 Bulging height-pressure curves

This phenomenon can be explained as follows. During the bulging process, the tube undergoes uniform deformation under bulging pressure. The material characteristics of the five sections are initially different. As hydro-bulging occurs, the deformation behaviors of these sections gradually become close to each other. These sections eventually converge as the inner pressure further increases.

The SEM images of the tube bulging fracture are presented in Fig. 9. The fracture position was close to the inner surface. The fracture morphology in the Fig. 9(a) clearly revealed the thinning of the said thickness before the fracture. The bulging fracture of the DC04-welded tube is a typical ductile fracture, as shown in Fig. 9(b). The dimples were clearly visible.

Fig. 9 Bulging fracture of the DC04-welded tube

3.4 Wall thicknesses at different bulging pressures

The tubes under different hydro-bulging pressure are shown in Fig. 10. The bulging heights and the wall thicknesses at the highest point were measured, as shown in Table 4.

Fig. 10 Tubes after bulging tests under different hydro-bulging pressures

Table 4. Wall thicknesses and bulging heights at different hydro-bulging pressures

Bulging Pressure (MPa)	15.26	16.66	16.78	17.61	19.08
Bulging height (mm)	1.49	2.55	3.20	4.14	5.36
Thickness (mm)	1.62	1.57	1.54	1.52	1.45

The comparison of wall thickness at the highest point between the calculated results Eq. (17) and experimental results is shown in Fig. 11. The maximum error between the calculation and experiment is 0.86%, which demonstrated that the mathematical analysis model can precisely predict the wall thickness of the highest point at different bulging pressures.

Fig. 11 Wall thicknesses at different bulging heights

4. Tube material characteristics analysis and discussion

The bulging height-pressure curve of the section E is obtained by the bulge test, as shown in Fig. 12(a). According to the analytical model and Eqs. (7)-(19), the equivalent strain-stress curve could be determined, as shown in Fig. 12(b).

Fig. 12 Bulge test results

The curves represent the deformation behaviors during THF. Two kinds of constitutive models, namely, the Ludwik constitutive model and the Swift constitutive model, are used to more accurately describe the tube material behaviors. These two constitutive models are illustrated in Table 5. Both models are utilized to fit the stress-strain curve (Fig. 13). The relatively simple Ludwik constitutive model is generally used to describe the material characteristics of tubes without pre-strain hardening; whereas the Swift constitutive model contains a pre-strain parameter

and is more suitable for revealing the material characteristics for tubes with roll bending.

Table 5. Ludwik and Swift material models and material parameters

Type	Constitutive model	Hardening exponent/ n	Strength coefficient/ K (MPa)	Pre-strain/ ε_0
Ludwik	$\sigma = K\varepsilon^n$	0.28	615.0	/
Swift	$\sigma = K(\varepsilon + \varepsilon_0)^n$	0.64	790.9	0.145

(a) Ludwik fitting curve

(b) Swift fitting curve

Fig. 13 Strain–stress fitting curves

5. Result assessment by FE simulations

FE simulations are conducted to evaluate the whole procedure of tube material characteristics.

The stress-strain curve obtained from the free-bulge test is used for simulation. The material parameters used in FE simulations can be evaluated. The strategy of result assessment by FE simulations is shown in Fig. 14.

Fig. 14 FE simulations strategy

5.1 FE model

The commercial software LS-DYNA was used to simulate the hydro-bulging process. The material model is Barlat's three-parameter plasticity model. The material parameters of the Ludwik and Swift models of the simulation are listed in Table 5. The Young's modulus was 207000 MPa, with a Poisson ratio of 0.28. The FE geometric model is meshed with shell element, as shown in Fig. 15. The tube is modeled by the size of its neutral layer and contains 1440 quadrilateral elements. The models of the punch and die contain 1368 quadrilateral elements and 232 triangle elements, respectively. The motion state of the die is defined as stationary, and the punch is movable along the axial direction. The hydro-bulging process includes two steps. First, the tube is flared and sealed by the punches. Subsequently, the hydro-bulging process is conducted. The simulation processes are shown in Table 6.

Fig. 15 FE model

Table 6. Contours of thickness distribution

Maximum height h_i (mm)	Flaring ($h = 0$)	$h = 1.03$	$h = 3.30$	$h = 5.17$
P_i for Ludwik model (MPa)	$P = 0$	$P = 15.6$	$P = 18.8$	$P = 19.8$
P_i for Swift model (MPa)	$P = 0$	$P = 16.8$	$P = 18.8$	$P = 19.9$

5.2 Results and discussion

Comparisons of the pressure-height curves between the simulation and the hydro-bulging test are shown in Fig. 16. Good agreement is achieved, and this finding implies the reliability of the constitutive models obtained by the hydro-bulging method. The predicted pressure-height curve based on Ludwik model is lower than that of the test when the bulging height is less than 1.5 mm because the pre-strain effect is disregarded in Ludwik model. The Swift model results in more efficient predictions than Ludwik model to simulate the whole hydro-bulging process.

(a) Ludwik model

(b) Swift model

Fig. 16 Comparisons of pressure-height curves between the simulation and the hydro-bulging test

5.3 Effects of anisotropy coefficient

The material characteristics of the tube during the bulge test can be precisely described by the stress-strain curve fitted by the Swift constitutive model and the anisotropy coefficients measured from the tensile tests of sheet blanks. The effect of the anisotropy coefficients on the tube bulging is discussed through FE simulations. The average anisotropy coefficients are set as $\bar{r} = 1, 1.4, 1.6$,

1.8. The predicted bulging height-pressure curves are shown in Fig. 17.

Fig. 17 Simulated results of tubes with different average anisotropy coefficients

The anisotropy coefficients have significant effects on the bulging pressure-height curves of tubes in the tube hydro-bulging. Lower pressure is needed at the same deformation of tubes with lower average anisotropy coefficients. To obtain the more accurate simulation results during hydro-bulging or tube bending process, the anisotropy coefficients should be considered in the tube material constitutive model.

6. Approximate determination method for the tube constitutive model

A comparison was conducted between the stress-strain curve of the sheet blank after translation and the stress-strain curve obtained by the hydro-bulge test, as shown in Fig. 18. The tube and the sheet blank have the similar hardening characteristics during large plastic deformation. The yield strength of the tube is higher than that of the sheet blank; this difference is attributed to the work hardening in the roll bending process.

Fig. 18 Comparison of the stress-strain curves

Therefore, an approximate determination method to determine the material characteristics of tubes from the sheet blanks is proposed by analyzing differences in the material Vickers hardness between sheet blanks and tubes. The yield strength of the material has a quantitative relationship with its Vickers hardness. Therefore, the yield strength of the tube can be obtained from the yield strength of the sheet blank and the Vickers hardness of the tube and the sheet blank; the yield strength is expressed as

$$\frac{H_T}{H_B} = \frac{\sigma_{sT}}{\sigma_{sB}} \quad (20)$$

The calculated average Vickers hardness of the tube and sheet blank are 106.3 kgf/mm^2 and 83.3 kgf/mm^2 , respectively. The yield strength of the sheet blank is 165 MPa; thus, the yield strength of the tube can be calculated as 210.6 MPa.

The approximate stress-strain curve of the welded tube can be obtained by intercepting the stress-strain curve of the sheet blank from the point Y of yield stress 210.6 MPa, as shown in Fig. 19(a). The stress-strain curve obtained by this approximate determination method is clearly similar to that obtained from the hydro-bulging test, as shown in Fig. 19(b).

(a) Stress-strain curve of the sheet blank (b) Approximate stress-strain curve of the tube

Fig. 19 Approximate determination method

The FE simulation was conducted with the stress-strain curve obtained from the approximate determination method to obtain the bulging pressure-height curve of the tube. The comparison between the bulging pressure-height curve from the abovementioned method and the curve from bulging test is made, as shown in Fig. 20. The simulation using the approximate determination method could obviously reproduce the real behavior of the tube.

Fig. 20 Bulging pressure-height curve of the FE simulation

Therefore, the material behavior of the 65 mm diameter DC04-welded tube can be represented by the stress-strain curve of the sheet blank. The initial yield point can be determined by the yield strength of sheet blank and Vickers hardness of the tube and sheet blank. An approximate stress-strain curve can be obtained with this approximate determination method. This curve could describe the material characteristics of the welded tube after working hardening.

7. Conclusion

The material behaviors of the tube and the hydro-bulging method are theoretically and experimentally studied. The relationship of material characteristics between the original sheet blank and tube is investigated. The main findings are summarized as follows:

(1) A mathematical analysis model is used to determine the material characteristics of the tube. This model considers the assumption of elliptical contours and the predictive equation of wall thickness. The effectiveness of the model is verified through FE simulation.

(2) The stress-strain curve of the DC04-welded tube can be obtained by using the analytical model and the tube hydro-bulging test. The anisotropy coefficients significantly affect the formability of tubes in THF. High inner pressure is essential for tubes with large anisotropy coefficients.

(3) During bulging, the tube likely undergoes uniform deformation because of the influence of bulging pressure. The Swift constitutive model is more suitable for describing the material characteristics of the DC04-welded tube attributed to the influence of pre-strain, especially when the bulging pressure is less than 17.5 MPa.

(4) An approximate determination method is proposed to provide a simple approach and to obtain the approximate stress-strain curve. Thus, this method can be used to describe the material characteristics of the welded tube after work hardening.

Acknowledgments

The authors would like to thank Mr. Kai Yang, Mr. Yisheng Zhang, Mr. Xiaowei Ma and Dr. Ningyu Ben for providing detailed experimental data. The authors would like to gratefully thank the Instrument Analysis Center of Xi'an Jiaotong University for assistance with SEM operation.

Author contributions

All authors contributed equally to the work.

Funding

This work was supported by the National Key R&D Program of China (No.2018YFB1106400), by the National Natural Science Foundation of China (No.51875441), and by the Fundamental Research Funds for Central Universities (No. xtr012019004 and zrzd2017027).

Data availability

The authors guarantee no restriction of availability of data, material, and code.

Compliance with ethical standards**Conflict of interest**

The authors declare that they have no conflict of interest.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent to publish

The publisher has the permission of the authors to publish the given article.

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