Experimental and numerical simulation investigation on tubular expansion process

Xiucheng Li¹, Shuai Ren¹, Dejun Li², Jingliang Wang¹, Xiao Li¹, Zhixing Wang¹, Chengjia Shang¹, *

¹University of Science and technology Beijing, Beijing, China
²Xi’an Sanhuan Science and Technology Development Corporation, Xi’an, China

*Corresponding author: xiuchengli@ustb.edu.cn

Abstract. Solid expansion technology has brought a revolution for oil and gas drilling and production. The performance of the expandable tubular is determined by the strength of material and the dimensional accuracy of the tube. In this study, the expansion pressures of two expandable tubulars at an expansion ratio of 15.0% were measured by full-scale tests. A 3D finite-element-method model was developed using Abaqus to dynamically simulate the expansion process of solid expandable tubulars. The simulated expansion pressures are in good agreement with experimental results, which proves the validity of the model. Based on the FEM model, the relationship between wall thickness uniformity after expansion and the strain hardening exponent of tubular material was investigated. The results show that the expandable tubular with a high strain hardening exponent can obtain more uniform wall thickness after expansion. The FEM model may be applied for design of expansion process and development of expandable tubulars in the future.

1. Introduction

Solid Expandable Tubular (SET) technology is a revolutionary drilling technology based on the concept of mono-diameter casing application [1-5]. The basic principle of the expandable tubular technology is to place the expandable tubular to the position reserved in the well and expand the diameter of the tubular to the required size by cold deformation. The cold deformation of the expandable tubular is a process in which the expandable cone driven by mechanical force causes radial plastic deformation of the tubular [6]. SET technology brought about revolutionary progress in oil and gas field exploitation and has been applied in many areas such as casing damage repair, completion, sealing formation, and tail pipe suspension [7-11]. Many studies have been reported [12-17] on expansion tubular, such as the influencing factors on expansion pressure [4, 18] and the change of wall thickness before and after expansion [3, 4]. However, very few studies were carried out on the wall thickness uniformity, which is also a key criterion for quality evaluation of expandable tubular. In this paper, the relationship between wall thickness uniformity and the mechanical properties of materials will be discussed. There have been extensive studies on the modeling of expandable tubular [17], [19-24], including mathematical calculation model [24], 2D shell model and 3D solid model. The 3D solid model is closest to the actual dynamic expansion process [19]. This paper establishes a 3D solid expandable tubular model for dynamic simulation.
In this paper, expansion experiments of two expandable tubular made from different materials were conducted to measure the expansion pressures. A 3D solid model was then established, which proves to reproduce the measured expansion pressure. Using the model, the relationship between wall thickness uniformity after expansion and strain hardening exponent of materials was studied.

2. Materials and methods

2.1. Materials.
Two expandable tubulars made from two different materials were selected for testing. The expandable tubular No. 1 has a microstructure of sorbite structure, as shown in Fig. 1. Expandable tubular No. 2 belongs to the category of TRIP steel and has a multiphase microstructure with ferrite, bainite and retained austenite, as shown in Fig. 2. The expandable tubulars are manufactured by straight seam electric resistance welding process, and their dimensions are listed in Table 1.

Table 1. Dimensions of solid expandable tubulars for the test.

| Tubular No. | Outer diameter/mm | Wall thickness/mm | Initial wall thickness uniformity |
|-------------|-------------------|-------------------|----------------------------------|
| 1           | 140.0             | 7.70              | 7.35%                            |
| 2           | 140.0             | 7.10              | 6.53%                            |

Fig 1. Microstructure of tubular No. 1.  
Fig 2. Microstructure of tubular No. 2.

Tensile tests were carried out according to API 5CT [25]. The tensile specimens were cut along the longitudinal direction of the tubulars. The dimensions of the tensile specimens are shown in Fig. 3. The tensile properties are listed in Table 2. The engineering stress-strain curves are shown in Fig. 4.

Fig 3. Dimensions of tensile specimens of expandable (unit: mm).
Table 2. Mechanical properties of the two expandable tubulars.

| Tubular No. | Yield strength | Tensile strength | Yield ratio | Uniform elongation | Total elongation | Strain hardening exponent |
|-------------|----------------|-----------------|-------------|--------------------|-----------------|--------------------------|
| 1           | 610            | 680             | 0.90        | 7.0%               | 29.0%           | 0.10                     |
| 2           | 320            | 509             | 0.63        | 16.0%              | 38.0%           | 0.23                     |

Fig 4. The engineering stress-strain curves of two expandable tubulars.

True stress-strain curves needed as input for the simulation were calculated from the engineering stress-strain curves. The true stress $\sigma_t$ can be calculated as a function of engineering stress $\sigma$ and strain $\varepsilon$ (Eq. 1 and Eq. 2).

$$\sigma_t = \frac{F}{A} = \frac{FV}{AA_0l_0} = \frac{FA}{A_0} \cdot \frac{l}{l_0} = \frac{F}{A_0} \cdot \frac{l_0(1+\varepsilon)}{l_0} = \sigma(1 + \varepsilon) \quad (1)$$

Where $F$ is the force, $l(l_0)$ and $A(A_0)$ are instantaneous (initial) length and cross sectional area of the specimen respectively. During plastic deformation the volume $V$ remains constant, thus the third equality holds. The true strain can be calculated as

$$\varepsilon_t = \int_{l_0}^{l} \frac{dl}{l} = \ln \frac{l}{l_0} = \ln(1 + \varepsilon) \quad (2)$$

These two equations are only applicable before necking and the data out of this range were extrapolated. The derived true stress-strain curves used in the FEM model are shown in Fig. 5.
2.2. Expansion test.
Expansion tests for the two expandable tubulars were performed on an independently designed expansion tester. The head of the expandable tubular was fixed to the tester through a flange. The expansion force was obtained by connecting the thread of the expansion cone to the tension rod of the tester. The dimensions of the expansion cone are shown in Fig. 6. The expansion pressure of the expandable tubular was recorded in real time by the tension sensor on the tester. Before the test began, grease was evenly applied to the inner wall of the tubular to reduce friction during expansion. The inner diameter and the wall thickness of the two tubulars were measured, and the inner diameter expansion ratio of both tubulars was 15.0%.
2.3. Establishment of the FEM model.
The dimensions of the cone shape were the same with those of the actual one. The geometry of the cone and pipe is shown in Fig. 7. The cross section of the tubular (Fig. 8) can be fitted to an elliptic equation (Eq. 3), to ensure that the values of wall thickness uniformity are the same for the FEM tubular model and the actual solid tubular. Wall thickness uniformity is defined by Eq. 4, where $t_{max}$, $t_{min}$ and $t_{avg}$ are the maximum, minimum and the average wall thickness of the tubular respectively.

$$\frac{(x-x_0)^2}{a^2} + \frac{(y-y_0)^2}{b^2} = 1$$ (3)

Wall Thickness Uniformity $= \frac{t_{max} - t_{min}}{t_{avg}} \times 100\%$ (4)

![Fig 7. The geometry of the cone and pipe used in the model.](image)

![Fig 8. Cross section of expandable tubular.](image)

Fixed-free boundary conditions (Fig. 9) were applied to simulate the expansion process. The constraints of the expansion tubular is shown in Fig. 10. Since the expansion cone is made from a material that is much stronger than that of the expandable tubular, the expansion cone is assumed to be rigid, which simplifies the problem.
3. Results and discussion

3.1. Verification of the FEM model.
The main output of this model is the expansion pressure. It can be seen from Table 3 that the expansion pressures predicted by the FEM model are in good agreement with the experimental results.

Table 3. Expansion pressure of two expandable tubulars and relative errors.

| Tubular No. | Material No. | Measured pressure/MPa | Simulated Pressure/MPa | Relative error |
|-------------|--------------|------------------------|------------------------|----------------|
| 1           | 1            | 34.5                   | 33.7                   | 2.21%          |
| 2           | 2            | 23.0                   | 22.1                   | 3.70%          |

3.2. Relationship between wall thickness uniformity after expansion and strain hardening exponent.
The wall thickness uniformity of Tubular No. 1 and No. 2 is 7.93% and 3.48% respectively, which means the latter has a better wall thickness uniformity. Among all the mechanical properties listed in Table 2, the strain hardening exponent is expected to be most relative to the wall thickness uniformity as it governs the amount of uniform plastic deformation. To verify that, five new expandable tubular models with different yield stresses but the same strain hardening exponent are constructed (Table 4), the true stress-strain curves of which can be found in Fig. 11. The equations of the outer and inner edges of the tubulars are shown in Eq. 5 and Eq. 6. The results show that the wall thickness uniformity will be the same when the strain hardening exponents are identical, which indicates the strong relevance between them.
Outer edge:

\[
\frac{(x-0.06)^2}{70.15^2} + \frac{y^2}{70.15^2} = 1
\]  

(5)

Inner edge:

\[
\frac{(x+0.06)^2}{62.01^2} + \frac{y^2}{62.01^2} = 1
\]  

(6)

**Fig 11.** The true stress-strain curves of materials 3, 4, 5, 6, 7.

**Table 4.** Properties of expandable tubular models No. 3, No. 4, No. 5, No. 6, No. 7.

| Tubular No. | Outer diameter/mm | Wall thickness/mm | YS/MPa | Initial wall thickness uniformity | Strain hardening exponent | Wall thickness uniformity after expansion |
|-------------|-------------------|-------------------|--------|----------------------------------|---------------------------|------------------------------------------|
| 3           | 140.0             | 8.14              | 250    | 5.0%                             | 0.10                      | 6.78%                                    |
| 4           | 140.0             | 8.14              | 300    | 5.0%                             | 0.10                      | 6.78%                                    |
| 5           | 140.0             | 8.14              | 350    | 5.0%                             | 0.10                      | 6.78%                                    |
| 6           | 140.0             | 8.14              | 400    | 5.0%                             | 0.10                      | 6.78%                                    |
| 7           | 140.0             | 8.14              | 450    | 5.0%                             | 0.10                      | 6.78%                                    |

Meanwhile, five more new materials (8, 9, 10, 11, 12) with different strain hardening exponents are simulated (Fig. 12) to further investigate the influence of strain hardening exponent on the wall thickness uniformity. For each material, three tubulars with different initial wall thickness uniformities (a: 3%, b: 5% and c: 10%) were modelled (Table 5). The relationship between the wall thickness uniformity and strain hardening exponent at different initial wall thickness uniformities are plotted in Fig. 13. It can be seen that the wall thickness will be more uniform with a higher strain hardening exponent.
**Fig 12.** The true stress-strain curves of materials No.8, 9, 10, 11, 12.

**Table 5.** Properties of expandable tubular models No.8a – No.12c.

| Tubular No. | Material No. | Outer diameter | Wall thickness | Initial wall thickness uniformity | Strain hardening exponent | Wall thickness uniformity after expansion |
|-------------|--------------|----------------|----------------|-----------------------------------|---------------------------|------------------------------------------|
| 8a          | 8            | 140.0          | 8.14           | 3%                                | 0.05                      | 5.26%                                    |
| 9a          | 9            | 140.0          | 8.14           | 3%                                | 0.10                      | 4.83%                                    |
| 10a         | 10           | 140.0          | 8.14           | 3%                                | 0.15                      | 4.45%                                    |
| 11a         | 11           | 140.0          | 8.14           | 3%                                | 0.20                      | 4.35%                                    |
| 12a         | 12           | 140.0          | 8.14           | 3%                                | 0.25                      | 4.16%                                    |
| 8b          | 8            | 140.0          | 8.14           | 5%                                | 0.05                      | 7.21%                                    |
| 9b          | 9            | 140.0          | 8.14           | 5%                                | 0.10                      | 6.78%                                    |
| 10b         | 10           | 140.0          | 8.14           | 5%                                | 0.15                      | 6.46%                                    |
| 11b         | 11           | 140.0          | 8.14           | 5%                                | 0.20                      | 6.25%                                    |
| 12b         | 12           | 140.0          | 8.14           | 5%                                | 0.25                      | 6.11%                                    |
| 8c          | 8            | 140.0          | 8.14           | 10%                               | 0.05                      | 11.82%                                   |
| 9c          | 9            | 140.0          | 8.14           | 10%                               | 0.10                      | 11.51%                                   |
| 10c         | 10           | 140.0          | 8.14           | 10%                               | 0.15                      | 11.27%                                   |
| 11c         | 11           | 140.0          | 8.14           | 10%                               | 0.20                      | 11.08%                                   |
| 12c         | 12           | 140.0          | 8.14           | 10%                               | 0.25                      | 10.92%                                   |
Fig 13. Relationship between wall thickness uniformity after expansion and strain hardening exponent at different initial wall thickness uniformities.

4. Conclusions
In this paper, full-scale tests and FEM modelling on two expandable tubulars were performed. The FEM model is able to simulate the dynamic expansion process and reproduce the experimentally measured expansion pressure. When the initial wall thickness and wall thickness uniformity are the same, the wall thickness uniformity after expansion is related to the strain hardening exponent of the material. The tubular with a high strain hardening index is more uniform in wall thickness after expansion. This finding provides guidance for the selection of expandable tubular materials in the future.

Acknowledgments
The authors acknowledge the financial supports from the National Key Technology R&D Program (2015BAE03B00) and Shell Global Solutions International B. V.

References
[1] Bourassa K A, Husby T, Watts R D, et al. Development, testing, and field deployment of a hydraulically expanded solid liner hanger in a casing directionally drilled well in norway[C]/IADC/SPE Drilling Conference. Society of Petroleum Engineers, 2008.
[2] Gorrara A, Hazel P, Tavendale F, et al. Development of a Gas-Tight External Casing Patch Using Direct Hydraulic Expansion of Standard Casing to Achieve a Permanent Load Bearing Connection[C]/SPE/IADC Drilling Conference. Society of Petroleum Engineers, 2005.
[3] Filippov A, Mack R, Cook L, et al. Expandable tubular solutions[C]/SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, 1999.
[4] Dupal K K, Campo D B, Lofton J E, et al. Solid expandable tubular technology-a year of case histories in the drilling environment[C]/SPE/IADC drilling conference. Society of Petroleum Engineers, 2001.
[5] Carstens C N, Strittmatter K B. Solid Expandable Tubular Technology: The Value of Planned Installation vs. Contingency [J]. SPE Drilling & Completion, 2006, 21(04): 279-286.
[6] Noel G. The Development and Applications of Solid Expandable Tubular Technology [J]. Journal
of Canadian Petroleum Technology, 2005, 44(12):12-15.

[7] Grant T, Bullock M. The evolution of solid expandable tubular technology: lessons learned over five years[C]/Offshore Technology Conference. Offshore Technology Conference, 2005.

[8] Morrison W, Al-Baggal Z, Baxendale R A, et al. Optimizing wellbore design using solid expandable tubular and bi-center bit technologies[C]/SPE Middle East Oil and Gas Show and Conference. Society of Petroleum Engineers, 2005.

[9] Cales G, Grant T, Book L. Reducing Non-Productive Time Through the Use of Solid Expandable Tubulars: How to Beat the Curve Through Pre-Planning[C]/Offshore Technology Conference. Offshore Technology Conference, 2004.

[10] Sparling S W, Noel G. Expanding Oil Field Tubulars Through a Window Demonstrates Value and Provides New Well Construction Option[C]/Offshore Technology Conference. Offshore Technology Conference, 2004.

[11] Gusevik R, Merritt R. Reaching deep reservoir targets using solid expandable tubulars[C]/SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, 2002.

[12] Al-Abri O S, Pervez T. Structural behavior of solid expandable tubular undergoes radial expansion process—Analytical, numerical, and experimental approaches [J]. International Journal of Solids and Structures, 2013, 50(19): 2980-2994.

[13] Fu J, Tang X, Zhou W, et al. Dynamic Analysis of Solid Expandable Tubular and Its Applications in Tahe Oilfield [J]. Arabian Journal for Science and Engineering, 2015, 40(8): 2437-2446.

[14] Wilson A. Study of Expandable-Tubular Collapse Leads To Risk-Based Strength Development [J]. Journal of Petroleum Technology, 2018, 70(06): 69-70.

[15] Zhang J, SHI T, Xu Q. Experiment Study of Longitudinal Metal Flow of Solid Expandable Tubular [J]. JOURNAL-SOUTHWEST PETROLEUM INSTITUTE, 2004, 26(2): 15-17.

[16] Binggui X, Yanping Z, Hui W, et al. Application of numerical simulation in the solid expandable tubular repair for casing damaged wells [J]. Petroleum Exploration and Development, 2009, 36(5): 651-657.

[17] Al-Abri O S. Analytical and numerical solution for large plastic deformation of solid expandable tubular[Ç]/SPÉ Annual Technical Conference and Exhibition. Society of Petroleum Engineers, 2011.

[18] Daigle C L, Campo D B, Naquin C J, et al. Expandable tubulars: field examples of application in well construction and remediation[Ç]/SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, 2000.

[19] Pervez T. Experimental and numerical investigations of expandable tubular structural integrity for well applications [J]. Journal of Achievements in Materials and Manufacturing Engineering, 2010, 41(1-2): 147-154.

[20] Pervez T, Seibi A C, Karrech A. Simulation of solid tubular expansion in well drilling using finite element method[J]. Petroleum science and technology, 2005, 23(7-8): 775-794.

[21] Binggui X, Yanping Z, Hui W, et al. Application of numerical simulation in the solid expandable tubular repair for casing damaged wells [J]. Petroleum Exploration and Development, 2009, 36(5): 651-657.

[22] Fu J, Tang X, Zhou W, et al. Dynamic Analysis of Solid Expandable Tubular and Its Applications in Tahe Oilfield [J]. Arabian Journal for Science and Engineering, 2015, 40(8): 2437-2446.

[23] Al-Abri O S, Pervez T, Al-Hiddabi S A, et al. Analytical model for stick–slip phenomenon in solid tubular expansion[J]. Journal of Petroleum Science and Engineering, 2015, 125: 218-233.

[24] Chen Jingjing, Li Dejun, Bai Qiang, et al. Calculation model of expansion force based on strain hardening behavior of expandable tubular [J]. Transactions of Materials and Heat Treatment, 2017,38 (08):151-158.

[25] Spec API. 5CT: Specification for casing and tubing [J]. 2011.