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Determination of stress–strain relationship of tubular material with hydraulic bulge test

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Abstract

Based on the plastic membrane theory and force equilibrium equations, etc., a unique approach is proposed with the curve fitting of experimental data to determine the stress–strain relationship of a thin-walled tube in hydroforming process (THF). A simple and practical hydraulic bulge test tooling was developed and free-bulged tests were performed on stainless steel and low carbon steel tubes to obtain required experimental deformation data. Finite element (FE) simulations of the free bulges were carried out to verify the approach indirectly. The results indicate that the present approach is accurate and acceptable to define the stress–strain behavior of tubular material, and furthermore, an extended flow stress curve with large strain can be obtained by the approach.

Keywords: Tube hydroforming; Stress–strain relationship; Hydraulic bulge test; Fe simulation

1. Introduction

Tube hydroforming (THF) is the process of forming tubular components by using hydraulic pressure as forming media. The main advantages of THF over conventional manufacturing techniques are enhanced component strength and rigidity, reduced weight and assembly costs by using common materials more efficiently, so it has enjoyed increasingly widespread applications in various fields, such as the automobile, aircraft and aerospace, and shipbuilding industries, etc. due to the need for stronger, lighter, and more precise parts [1,2].

Material mechanical property plays a major role in THF and is of paramount importance to the success of the THF process. Previous researches have revealed that material property has large impact on the magnitude of internal forming pressure, loading path, bulge height, wall thickness distribution, bulge profile and die filling ability [3,4]. On the other hand, finite element method (FEM) is widely used for simulation of the process; however, finite element (FE) simulation demands a reliable stress–strain relationship which is able to describe the plastic deformation behavior of a tubular material in THF, and the resulting accuracy of FE simulation is strongly dependent on the material model parameters such as material strength coefficient K-value and strain-hardening exponent n-value [5,6]. Unfortunately, THF is a relatively new technology as compared with the conventional stamping processes so that there is no large mechanical data for tubular materials commonly used in THF. Accordingly, an accurate approach is needed to define the stress–strain property of a tube for assisting engineers to improve the capability of THF.

Thanks to its simple and easy implementation, the uniaxial tensile test is widely used to determine material parameters and stress–strain relationship. However, direct introduction of the data primarily derived from uniaxial tensile test of a flat sheet, from which the tube is rolled, into the THF analysis may give rise to unacceptable discrepancy. That is due to the happening of the strain hardening and anisotropy during the rolling and bending operation used to manufacture the tube, as well as the different stress state encountered in the tensile test (in uniaxial stress state) and in THF (in biaxial stress state), etc. [7]. As a result, to

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obtain reliable material parameters and stress–strain relationship of a tube for THF, a testing method which must simulate the testing conditions as closely as possible to real THF processes should be used, i.e. a biaxial testing should be conducted on a tubular geometry rather than on a flat sheet. Thus hydraulic tube bulge test is mostly preferable and recommended [5,6].

Several hydraulic tube bulge test procedures have been proposed so far [8,9]. The main problem of using the hydraulic bulge test for determining the stress–strain relationship is the measurement of the meridian radius (r_φ) of curvature of deforming tube (see Fig. 1)), which is required to calculate stress components on the basis of force equilibrium equations. Consequently, the system of tube bulge testing must be equipped with devices capable of measuring the meridian radius. This may result in an increase of cost, difficulty in manipulation and an unpractical use in press shops. Worse of all, it has been proved to be difficult to obtain a good precision in the measurement of the meridian radius in some cases, thus causing a loss of accuracy in stress–strain relationship [3].

Several alternative procedures to avoid a direct measurement of the meridian radius have been proposed. In these procedures the radius is not measured, but calculated by assuming an analytical shape function for the bulge profile in the free-bulged region. For instance, based on the force equilibrium equations and the assumption of an elliptical surface for the bulge profile, Hwang et al. [1] deduced mathematical expressions for meridian radius and thickness distribution, while Tirosh et al. [10,11] did on the basis of an energy balance and the assumption of cosine-like functions for outer and inner bulge profiles. However, owing to the fact that the material property has considerable effect on the bulge profile, the accuracy of the results might be limited. Sokolowski [7] proposed a desirable hydraulic bulge test for determining the stress–strain relationship of tubular materials by taking force equilibrium law and least squares curve fitting techniques. However, the thickness data at various axial locations have to be measured to calculate the stress components.

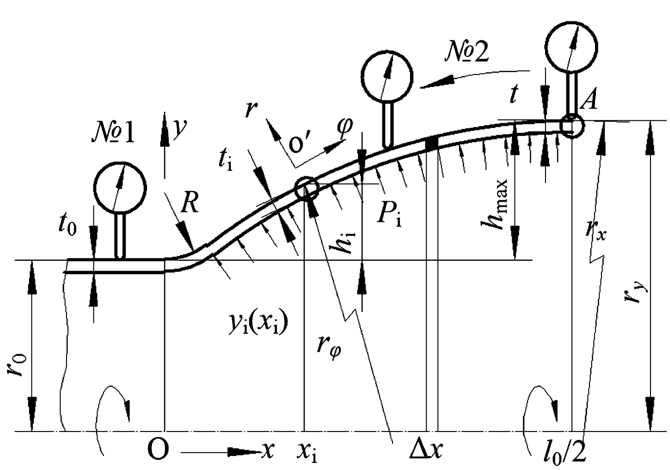

Fig. 1. The schematic of free hydraulic bulging with designations. The local coordinate system is denoted by φ (meridian) and r (radial). The θ-axis (circumferential) is perpendicular to φ- and r-axis using the right-hand rule. R is entry radius of the supporting die. The relationship between the bulge height (h_i) and the bugle radius is given by $y_i = h_i + r_0$.

The objective of this study was to present a unique approach for determining the stress–strain relationship of tubular material from a hydroforming point of view (in biaxial stretching condition), and to suggest a material testing and parameter identification procedure as well suited for THF. Free-bulged tests were carried out with a self-constructed hydraulic bulge test tooling to gather experimental data required for constructing the stress–strain relationship, and FE simulations of the hydraulic bulging were performed in order to verify the approach. By the approach, which is based on the force equilibrium equations and experimental data, the meridian radius is not measured but calculated by taking curve-fitting algorithm techniques. Moreover, it eliminates the necessity of the site measurements of the thicknesses, strain and stress distribution at various axial locations.

2. Analytical approach

The schematic of free hydraulic bulging is shown in Fig. 1, where a thin-walled round tube is under expansion in an open die by a hydraulic pressure, i.e. internal pressure (P_i). Due to the axi-symmetry, it deals with a quarter of the specimen with a gage length l_0 of free-bulged region. It is assumed that the stress and strain distribute uniformly in the radial (r) or thickness direction and the radial stress (σ_r) is equal to zero owing to the small tube wall thickness ($t_0/r_0 < < 1$). According to membrane theory the force equilibrium equation for an element at the free-bulged region can be written as

$$\frac{\sigma_\theta}{\rho_\theta} + \frac{\sigma_\varphi}{\rho_\varphi} = \frac{P_i}{t_i}, \tag{1}$$

where t_i is the current wall thickness, ρ_θ and ρ_φ are the circumferential (hoop) and meridian radii of curvatures at the element, and σ_θ and σ_φ are the circumferential and meridian stress components at the element, respectively.

The endeavor to directly measure the stress and strain on the three-dimensional surface of deformed tube, as well as the meridian radius of curvature at various axial locations is not only troublesome and difficult, but also inaccurate, as mentioned previously. In present study the analytical means derived by Fuchizawa [8] are adopted to estimate the stress–strain relationship of a tubular material. The equations derived for present approach are based on the central location of the bulge profile of the deformed tube, or point A as shown in Fig. 1. By taking equilibrium of static forces at the central location, the following equations are derived [8]

$$\sigma_x = \frac{P_i(r_y - t)^2}{2t(r_y - t/2)}, \tag{2}$$