International Journal of Mechanical Sciences 87 (2014) 307–315

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Analytical model for tube hydro-bulging tests, part II: Linear model for pole thickness and its application

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ARTICLE INFO

Article history:
Received 15 June 2013
Received in revised form
13 April 2014
Accepted 7 May 2014
Available online 27 May 2014

Keywords:
Thin-walled tube
Hydro-bulging test
Stress–strain curve
Bi-axial stress state
Tube hydroforming

ABSTRACT

Hydro-bulging test is a specialized method to obtain the mechanical properties of tubular materials, which is very important for the cases when tubular blank is formed under bi-axial stress states. However, this test is currently applied with different testing conditions and analytical models. In addition, the deformation is often interrupted in order to measure the pole thickness change during testing, which may has considerable effect on final results obtained. Based on the models for stress components and bulging zone profile presented in an accompanying paper, i.e., Part I [19], analytical model for pole thickness during hydro-bulging test is presented and analyzed. A linear model for pole thickness change is proposed for the first time, and is successfully validated by experiments of AA6061 aluminum tube and SUS409 steel tube. Based on the linear model, the difficulty for pole thickness measuring during hydro-bulging is conquered. Then, a new testing method termed as *linear-model based hydro-bulging test*, is developed and applied for extruded aluminum alloy tube and roll-welded steel tube. It is demonstrated that the new testing method is more feasible and effective in characterizing the deformation behavior of tubular materials under bi-axial stress states.

1. Introduction

For isotropic material which also workhardens isotropically, it is sufficient to test the mechanical properties along one direction. However, extruded aluminum tube is highly anisotropic. Both the ductility and the mechanical properties along axial direction and hoop direction are obviously different [1–3]. No accurate data in hoop direction can be obtained if traditional uniaxial tensile test is used, because work hardening in specimen preparation will cause considerable errors in characterizing the mechanical properties, especially for tube with small radius. So-called ring hoop tension test (RHTT) was developed to determine the properties of tubes along circumferential direction, in which ring specimen can be stretched directly using two D-blocks [4–6]. Unfortunately, the strength of the specimen is often overestimated due to the friction force between D-blocks and specimen [7].

In hydroforming process, the material deforms mainly in a biaxial stress state. Considering the anisotropic character of extruded tube, its formability and deformation behavior are related with the stress state. That means uniaxial test is no longer effective for characterizing the properties of tube, and multi-axial and/or multistage loading tests are infinitely preferable instead. The responses of materials to a variety of loading modes have been of interest for at least a century [8]. A servo-controlled tension-internal pressure testing machine was designed and built to investigate the deformation of tubular materials [9]. Measurement of biaxial stress–strain curves of tubular materials or sheet metals under biaxial tension can be realized [10,11]. Hydro-bulging test of tube is also often conducted using a relatively simple set-up [12–16]. Equivalent stress–strain relations determined by hydro-bulging test can be used to describe the properties of tubular materials for industrial application, in which the tubes deform in a similar biaxial stress state.

In order to obtain the equivalent stress–strain curve of tubular materials under bi-axial stress state by hydro-bulging test, an analytical model for stress components and strain components is required. For stress and strain components determination, the ends constraining condition and appropriate analytical model should be clarified first. Then the curvature radius at the central point in bulging zone should be directly measured [17,18], or predicted according to the measured bulging displacement in conjunction with an assumption of profile curve for bulging zone [19,20]. In an accompanying paper titled "*Analytical model for tube hydro-bulging tests, part I: models for stress components and bulging*

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http://dx.doi.org/10.1016/j.ijmecsci.2014.05.010
0020-7403/

zone profile", a unified analytical model for stress components calculation has been proposed for closed-end and fixed-end conditions. A die-related ellipsoid model has been presented and well verified by experiments, for determining the curvature radius at the analytical point [21].

The thickness at the central position of bulging zone during hydro-bulging, often called *pole thickness*, is also required for stress and strain calculation. Currently, the pole thickness during hydro-bulging can be measured directly or calculated according to analytical models. Ultrasonic thickness transducer is often used to measure the pole thickness continuously [12]. The measuring accuracy maybe affected by the pressure medium in the tube, also there is a lack of special probe for curved surface. A self-designed measuring mechanism with a dial-gauge was used to measure the thickness, in order to get a direct result of pole thickness [13,14]. However, the hydro-bulging test should be stopped and the internal pressure released for each measuring. That means, several loading and un-loading process occurred in one hydro-bulging test, which will inevitably change the deformation behavior of tubes. In order to avoid discontinuous measurement, multi-samples methods were used instead, in which several tubular specimens are expanded to different bulging height separately, and then measured [17]. This method can reduce the effect of discontinuous loading, however, the difference of original tube thickness and the properties variance will cause uncertain effect on final results. Ben Ouirane et al. [22] discussed the influence of major parameters on the accuracy of the hardening curve obtained from the tube bulging test . Calculating pole thickness has also been proposed based on a simple assumption of bulging zone profile and volume constancy [13].

As the data of pole thickness is used directly for calculation of both stress components and strain components, it is crucial to improve the accuracy of pole thickness. In fact, the error of pole thickness and its consequent effect on the calculated stress–strain curve may counteract the advantage of hydro-bulging test over traditional uniaxial tensile test, and make all the efforts of hydro-bulging test meaningless.

In this study, based on the analytical model for stress components and geometrical model for bulging-zone presented in the accompanying paper titled "*Analytical model for tube hydro-bulging test, part I: models for stress components and bulging zone profile*" [21], the variation of pole thickness during hydro-bulging test will be discussed. The linear model for pole thickness is proposed for the first time, and then validated by experiments. A new testing method based on the linear model for pole thickness is developed consequently, and applied for both extruded aluminum alloy tubes and roll-welded steel tube.

2. Principle of tube hydro-bulging test

During hydro-bulging test, the bulging height h, thickness t_p and shape of central bulging zone are needed for calculating the stress and strain components. Fig. 1 shows the stress analysis of the central point P in bulging zone. In the figure, ρ_θ and ρ_z, σ_θ and σ_z, are curvature radii and stresses in hoop and axial directions, respectively.

Strain components at point P along with hoop and radial directions can be given as:

$$\varepsilon_\theta = \ln\left(\frac{R_P - t_p/2}{R_0 - t_0/2}\right) = \ln\left(\frac{h + R_0 - t_p/2}{R_0 - t_0/2}\right) \tag{1}$$

$$\varepsilon_t = \ln\left(\frac{t_P}{t_0}\right) \tag{2}$$

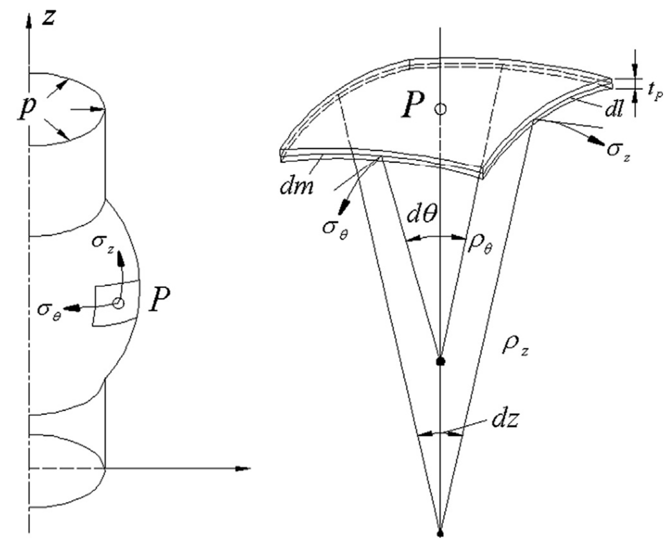

Fig. 1. Stress analysis at the central position of bulging zone.

where, R_P is the outer radius at point P.

It can be seen that the strain components can be calculated if the bulging height h and pole thickness t_p are given during a hydro-bulging process.

According to the equilibrium of shell element in Fig. 1, the Laplace's equation can be given as follows [23]:

$$\sigma_z \frac{t_P}{(\rho_z - t_P/2)} + \sigma_\theta \frac{t_P}{(\rho_\theta - t_P/2)} = p \frac{(\rho_z - t_P)(\rho_\theta - t_P)}{(\rho_z - t_P/2)(\rho_\theta - t_P/2)} \tag{3}$$

It can be seen that curvature radii ρ_θ and ρ_z, pole thickness t_P and bulging height h at point P are required for calculating the equivalent stress–strain curve, besides the internal pressure$p$. Internal pressure p and bulging height h can be measured directly. The value of ρ_z depends on the assumption of bulging zone profile, and$\rho_\theta = R_P = R_0 + h$. Pole thickness t_P can be measured directly or calculated according to analytical models.

For characterizing the mechanical behavior of materials under multi-axial stress state, equivalent stress–equivalent strain curves are usually determined. If only the transverse anisotropy of extruded tubular materials is considered, Hosford yield function based on crystal plasticity for plane stress problem can be given as follows [8]:

$$f = \sigma_i^M = \frac{1}{(1+r^*)}\left[|\sigma_\theta|^M + |\sigma_z|^M + r^*|\sigma_\theta - \sigma_z|^M\right] \tag{4}$$

where, $M = 6$for BCC materials and $M = 8$ for FCC materials, $r^*$is the transverse anisotropic coefficient.

Then the equivalent stress $\sigma_i$can be expressed as:

$$\sigma_i = \left\{\frac{1}{(1+r^*)}\left[|\sigma_\theta|^M + |\sigma_z|^M + r^*|\sigma_\theta - \sigma_z|^M\right]\right\}^{\frac{1}{M}} \tag{5}$$

Assuming that the tubular material is under bi-tension stress state and hoop stress is bigger than axial stress, i.e., $\sigma_\theta > \sigma_z > 0$. Then according to Drucker's associated flow rule, the strain increments can be given as:

$$\begin{cases} d\varepsilon_\theta = \frac{\partial f}{\partial \sigma_\theta} d\lambda = \frac{M}{(1+r^*)}\left[\sigma_\theta{}^{M-1} + r^*(\sigma_\theta - \sigma_z)^{M-1}\right] d\lambda \\ d\varepsilon_z = \frac{\partial f}{\partial \sigma_z} d\lambda = \frac{M}{(1+r^*)}\left[\sigma_z{}^{M-1} - r^*(\sigma_\theta - \sigma_z)^{M-1}\right] d\lambda \end{cases} \tag{6}$$

By the definition of incremental plastic work per unit volume, the equivalent plastic strain increment can be expressed as:

$$d\varepsilon_i = \frac{\sigma_\theta d\varepsilon_\theta + \sigma_z d\varepsilon_z}{\sigma_i} \tag{7}$$