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The determination of flow stress of tubular material for hydroforming applications

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ABSTRACT

Tube hydroforming (THF) process is nowadays a developed and successful way for forming of complex shapes with less operations required compared to conventional tube forming processes. FE simulations are powerful tools which allow a remarkable saving in time and money when developing a feasibility study or a prototype phase for a new THF operation. However the successful use of FE simulations depends on several factors such as interface friction or material properties. While in the past flow stress used as input in FE simulations was generally obtained from tensile test conducted on the sheet prior to rolling and welding operations in case of rolled and welded tubes, or tensile test conducted on the whole tube for extruded or seamless tubes, in the last years tube bulge test has been widely used. In this research test experiments, coupled with suitable analytical model of the process, are used to identify the flow stress of tubes (under biaxial stress state) by measuring geometrical features of the tube under study as the fluid pressure increases. In the present paper a new approach to tube bulge test is described. The innovative aspect is related to the fact that the tube ends are blocked and so the equilibrium expression in axial direction normally used to calculate stresses is no more valid. The stress state is therefore derived from the flow rule and the volume constancy.

The new proposed analytical model was validated by means of FE simulations. Results of test conducted on seamless tubes show that bulge test allows to obtain material properties for high strain thus avoiding possible errors in extrapolating flow stress for FE simulations.
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1. Introduction

Nowadays, the development of a successful tube hydroforming (THF) process is strictly dependent on a successful use of finite element (FE) simulations. However the correct use of FE simulations requires an accurate knowledge of material properties given as an input to the FE software. Tubular material properties are generally obtained from the tensile test conducted on specimens cut from the sheet prior to rolling and welding operations (in case of rolled and welded tubes), or, where possible, on specimens directly cut from the tube. Sometimes, especially for seamless or extruded tubes where there are no other data available, tensile tests are performed on the whole tube. However, the use of tensile test data in FE simulations introduces approximations since the maximum strain obtained in uniaxial tensile test before necking is small compared to strains achievable during a THF process. Moreover, while the stress state in tensile test is uniaxial, it

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becomes multiaxial (either only expansion or expansion and compression) during a THF process. Also, in case of tubes obtained from thin sheets rolled and welded, the rolling and welding operations conducted reduce the tube formability, so that its behavior will be different with respect to the original sheet. Tensile test is also inadequate for the evaluation of tubular formability and evaluation of the quality of incoming tubes in a manufacturing plant. Tube bulge test is a testing method which is able to overcome the aforementioned problems, since it provides a better approximation of the stress state encountered during a real THF process compared to the uniaxial tensile test.

Tube bulge test was first investigated by Woo et al. (Woo and Hawkes, 1968; Woo, 1973). It was found that in a tube subjected to internal pressure and axial compressive forces, the strain of the material before failure could be greatly increased, concluding that stress–strain characteristics for tube should be determined by bulge test. Same conclusion was also drawn by Fuchizawa et al. (Fuchizawa and Narazaki, 1993; Fuchizawa, 1987), however in this case ends of the tube were restrained by a set of dies at a predetermined length. One of the supporting dies was still while the other one was free to move in order to reduce the axial stretching on the tube.

Altan et al. (Sokolowsky et al., 2000; Strano and Altan, 2004; Muammer et al., 2001; Hwang et al., 2007) developed a procedure similar to the one proposed by Fuchizawa, however in this case both the tube ends were fixed in axial and radial displacement. Koc et al. (2000) investigated different methods to conduct the tube bulge test depending whether the parameters required for the calculation of the stress–strain relationship (longitudinal and circumferential radius of curvature, bulge height, internal pressure and thickness at the top of the dome) are measured on-line or off-line.

In the present study a new analytical approach for describing the tube bulge test with fixed tube edges, is presented. Experiments were conducted on annealed 25 Cr Mo 4 seamless tubes with 40 mm external diameter and 2 mm wall thickness, using the hydroforming equipment available at the University of Brescia (Giardini et al., 2005; Attanasio et al., 2006). Validation of the developed analytical–experimental procedure, by means of FE simulations, is also reported.

2. Analytical approach

In this section the analytical procedure for the determination of tubular material properties, using bulge test, is presented. Tubes used in this study are considered to have small thickness compared to the external diameter. Therefore stress in the thickness direction (σ_t) is considered negligible compared to the hoop (σ_ϑ) and longitudinal (σ_z) stresses, allowing the membrane theory to be used. The peculiarity of the test is that the tube ends are fixed so that any movement in the axial direction is neglected. Fig. 1 shows the state of stress of an element at the top of the dome during bulge test and Fig. 2 shows the geometry of a deformed tube and how the tube edges are blocked. The equilibrium for the element at the top of the dome can be normally

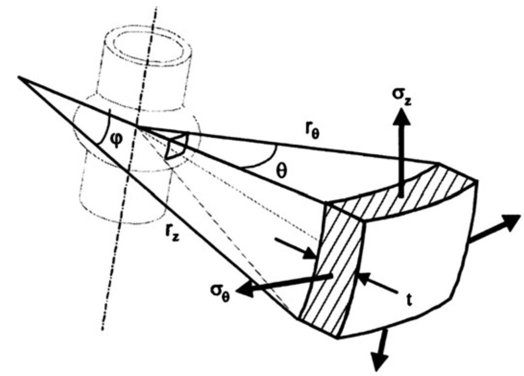

Fig. 1 – State of stress of an element at the top of the dome during bulge test.

written as

$$\frac{\sigma_\vartheta}{r_\vartheta} + \frac{\sigma_z}{r_z} = \frac{p}{t} \tag{1}$$

where r_ϑ is the curvature radius in the hoop direction, r_z is the curvature radius in the longitudinal direction, p is the fluid pressure acting on the tube and t is the tube thickness.

Since in the realized equipment the tube edges are fixed, it is not possible to express σ_z as function of the equilibrium condition along the longitudinal direction as done by several authors (Hwang et al., 2007). The new approach consisted in deriving σ_z from the equilibrium equation (1) and in using the flow rule to calculate σ_ϑ.

This means that from Eq. (1) the longitudinal stress can be derived as

$$\sigma_z = \left(\frac{p}{t} - \frac{\sigma_\vartheta}{r_\vartheta}\right) r_z \tag{2}$$

Relationships between stress and strain in each direction (i.e. the flow rule) are based on the assumption of a strain path proportional to the corresponding deviatoric stress (the stress component responsible of the plastic work). In relation (3) the incremental strain is considered proportional to the total plastic strain (Hosford and Caddell, 1983). Neglecting σ_t and considering an isotropic material, it can be written that

$$\frac{d\varepsilon_\vartheta}{\sigma'_\vartheta} = \frac{d\varepsilon_t}{\sigma'_t} = \frac{d\varepsilon_z}{\sigma'_z} \rightarrow \begin{cases} d\varepsilon_\vartheta = \partial\lambda\left(\sigma_\vartheta - \frac{1}{2}(\sigma_z + \sigma_t)\right) \\ d\varepsilon_z = \partial\lambda\left(\sigma_z - \frac{1}{2}(\sigma_\vartheta + \sigma_t)\right) \\ d\varepsilon_t = \partial\lambda\left(\sigma_t - \frac{1}{2}(\sigma_z + \sigma_\vartheta)\right) \end{cases} \rightarrow \frac{d\varepsilon_\vartheta}{\sigma_\vartheta - (1/2)\sigma_z}$$

$$= \frac{d\varepsilon_z}{\sigma_z - (1/2)\sigma_\vartheta} \rightarrow \frac{\varepsilon_\vartheta}{\sigma_\vartheta - (1/2)\sigma_z} = \frac{\varepsilon_z}{\sigma_z - (1/2)\sigma_\vartheta} \tag{3}$$

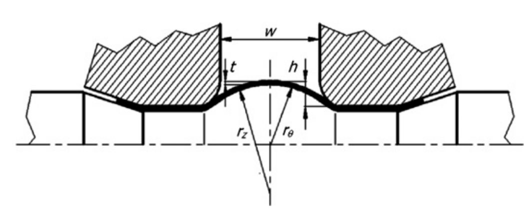

Fig. 2 – Geometry of a deformed tube.

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