Steel And Copper Flow Stress Determination for THF Applications

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ABSTRACT: Tube hydroforming (THF) process is nowadays a developed and successful way for forming complex shapes with less operations required compared to conventional tube forming processes. Since THF is a recently developed technology, there is a lack of knowledge on the process which can be overcome by using FE simulations. In fact, simulation allows a remarkable saving in time and money when developing a feasibility study or a prototype for new THF operations. The reliability of FE simulations depends on several factors such as interface friction and material properties. The classical method used for evaluating the material flow stress is the tensile test. This is a simple test which stresses the material in only one direction, differently from the actual tube stress state in THF. A biaxial stress state can be achieved by using the tube bulge test, which, consequently gives more reliable data for determining the material flow stress. The present paper describes the experiments and the analytical model of tube bulge test for the identification of the flow stress under a biaxial stress state. The innovative aspect of the proposed approach is related to the fact that the tube ends are blocked and, in the analytical model, the stress state is derived from the flow rule and the volume constancy. The experimental data of bulge curvature and tube thickness are used by the analytical model to calculate the material stress-strain relation. Results of tests conducted on different tube materials show that bulge test allows to obtain material properties for high strain thus avoiding possible errors in extrapolating flow stress for FE simulations.

Key words: Tube bulge test, flow stress determination, FE simulations

1 INTRODUCTION

The recent researches on tube hydroforming (THF) highlighted how process optimization has to be carried out by means of finite element simulations in order to shorten the trial-and-error phases which are time and cost consuming.

It is important to point out that the reliability of FEM results depends on the quality of the input data and, between them, the knowledge of material properties plays a fundamental role.

Tubular materials properties are generally obtained from tensile tests conducted either on sheet (prior to rolling and welding operations in case of rolled and welded tubes), or directly from the tube. The use of tensile test data in FE simulations introduces approximations since the maximum strains obtained in uniaxial tensile test before necking are small compared to those achieved during a THF process. Moreover, in this case a multiaxial stress state is realised. For this reason tube bulge test provides a better approximation of the stress state encountered during actual THF processes. Many Authors have already dealt with the problem of tube bulge test [1-2] and different test configurations and analytical description have been proposed [3-9].

In the present study a new analytical approach for determining the material flow stress is presented. Its innovative aspect is that the tube ends are blocked and the stress state is derived from the flow rule and the volume constancy [10]. Experiments were conducted on seamless (copper) and welded (aluminised steel) tubes, using the hydroforming equipment available at the University of Brescia labs [10-12]. The validation of the proposed procedure was carried out through FE simulations [10].

2 THE EXPERIMENTAL EQUIPMENT

The equipment for THF testing has been designed so to be adapted to the hydroforming machine previously developed by the authors, paying particular attention to flexibility and changeability of the components. In this way, it is possible to set up the tests according to different tube thicknesses and diameters and considering different bulge length. Figure 1 shows the main components of the equipment. For the proposed bulge test the tube ends are fully blocked due to the action of two conical shaped actuators (45°) which avoids fluid leakage, too. As a consequence the tube axial movement is not allowed and the deformation is fully localised in the bulge area (*w*) as shown in figure 2. During the tests the dies are locked by means of six screws.

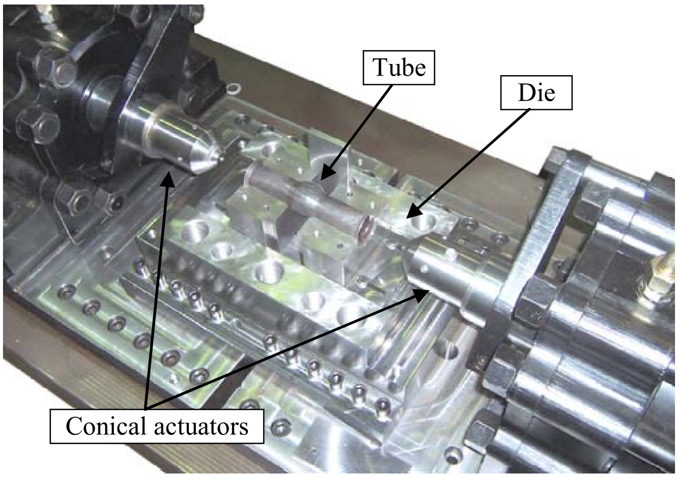

Fig. 1. THF equipment components.

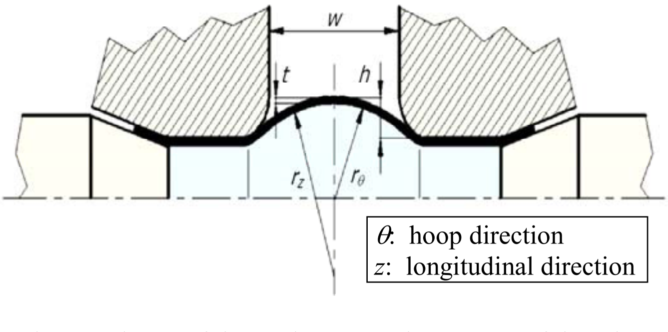

Fig. 2. Scheme of the equipment and geometry of the tube.

To determine the tube flow stress it is necessary to perform several tests at different pressure levels measuring the final bulge height (*h*), thickness (*t*) and longitudinal curvature radius (r_z) of the tube.

The different pressure levels are set as a fraction of the bursting pressure. Each test is carried out on a different tube and is repeated in order to take into account the process variability.

3 THE ANALYTICAL MODEL

The analytical procedure for tubular material properties determination using bulge test, is based on the radial equilibrium equation of an element at the top of the bulging dome (which allow to calculate σ_z) and on the following assumptions:

- the tubes thickness is small compared to the external diameter, thus the stress in the thickness direction can be considered negligible with respect to σ_ϑ and σ_z
- since in the realized equipment the tube edges are fixed, σ_ϑ is derived from the flow rule [10,13]
- the material is considered isotropic
- hoop and thickness strains are evaluated from the thickness and the curvature radii of the deformed tube.

Finally, the longitudinal stress σ_z and the hoop stress σ_ϑ can be calculated as [10]:

$$\sigma_z = \left(\frac{p}{t} - \frac{\sigma_\vartheta}{r_\vartheta} \right) \cdot r_z \tag{1}$$

$$\sigma_\vartheta = \frac{p r_\vartheta r_z}{t} \cdot \left(\frac{1 + 2\dfrac{\varepsilon_\vartheta}{\varepsilon_z}}{2r_\vartheta + r_z + \dfrac{\varepsilon_\vartheta}{\varepsilon_z} \cdot \left(2r_z + r_\vartheta\right)} \right) \tag{2}$$

While deformations can be expressed as:

$$\varepsilon_\vartheta = \ln \frac{r_\vartheta}{r_0} \text{; } \varepsilon_t = \ln \frac{t}{t_0} \text{; } \varepsilon_z = -\left(\varepsilon_\vartheta + \varepsilon_t\right) \tag{3}$$

Therefore, in order to evaluate stresses and strains during bulge test, the instantaneous thickness (*t*), the radii of curvature along longitudinal (r_z) and hoop (r_θ) directions and the internal pressure (*p*) are required.

Once all the stresses and strains are calculated, the equivalent stress and equivalent strain can be evaluated using Von Mises yield criterion under isotropic conditions. Conducting several experimental tests using different internal fluid pressures, it is possible to obtain a set of ($\bar{\sigma}, \bar{\varepsilon}$) couples representing the experimental stress-strain relationship of the material during bulge test. These values, plotted in a $\bar{\sigma}, \bar{\varepsilon}$ diagram, can be fitted by means of the Krupkowsky's law, so obtaining an equation useful for representing the material behaviour in FE simulations:

$$\bar{\sigma} = K \cdot \left(\varepsilon_0 + \bar{\varepsilon}\right)^n \tag{4}$$

4 EXPERIMENTAL RESULTS

As already said, the experimental campaign was carried out on copper and aluminised steel tubes.

The experiments were conducted at different pressure levels in order to obtain the equivalent stress-strain relationship. A circle grid was etched on each tube to measure the hoop and the longitudinal deformations at the end of the process so to verify the deformations calculated by the analytical model. Figure 3 shows the copper and aluminised steel tubes at the end of the process. The bulge area and the tube ends are plastically deformed. During the test the axial actuators are still and the tube is fully blocked.

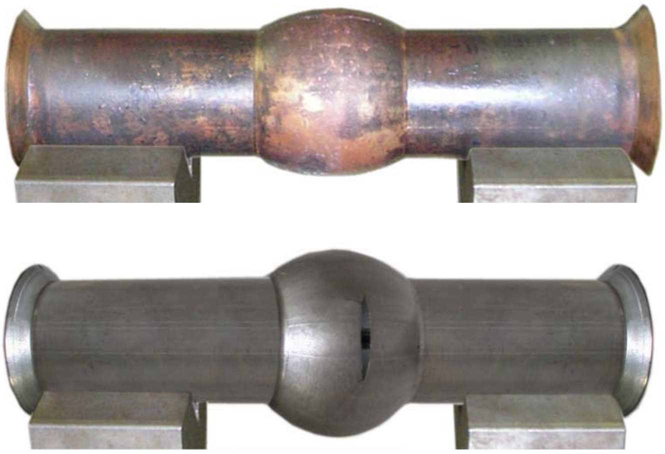

Fig. 3. Copper and aluminised steel tubes at bursting.

The experiments design starts from the observation of the tube bursting pressure and yield pressure. Within this range other different pressure levels have been investigated. For each tested tube the bulge height, the radius of curvature in the longitudinal direction and the wall thickness were measured.

From these experimental values, the stress-strain relationships were derived applying a fitting algorithm.

4.1 Tests on copper tubes

The tests on copper tubes (42 mm diameter, 1 mm thickness) have been carried out at different pressure levels as reported in table 1. The $\bar{\sigma}_{avg}$ and $\bar{\varepsilon}_{avg}$ average values, calculated from the tubes measurements, are reported too. Figure 4 shows the experimental data and the interpolating law:

$$\bar{\sigma} = 556.50 \cdot \left(0.061 + \bar{\varepsilon}\right)^{0.76} \tag{4}$$

4.2 Tests on steel tubes

The steel tube material is the aluminised steel DX 53 + AS120. The tube external diameter is 42 mm and the thickness is 1.2 mm. The pressure levels used in the tests are reported in table 2 together with the correpsonding $\bar{\sigma}_{avg}$ and $\bar{\varepsilon}_{avg}$ values. Figure 4 shows the experimental data and the interpolating law:

$$\bar{\sigma} = 682 \cdot \left(0.054 + \bar{\varepsilon}\right)^{0.34} \tag{5}$$

Table1. Copper tube testing pressures and obtained results

Pressure level	Test Pressure [MPa]	$\bar{\sigma}_{avg}$ [MPa]	$\bar{\varepsilon}_{avg}$
#1	5.8	116.64	0.067
#2	7.2	157.79	0.129
#3	7.9	174.26	0.158
#4	8.6	195.11	0.194
#5	9.3	206.81	0.177
#6	9.9 (bursting)	244.06	0.277

Table2. Aluminised steel tube testing pressures and obtained results

Pressure level	Test Pressure [MPa]	$\bar{\sigma}_{avg}$ [MPa]	$\bar{\varepsilon}_{avg}$
#1	19.1	341.27	0.076
#2	21.8	408.46	0.172
#3	22.5	441.37	0.224
#4	23.9	498.53	0.302
#5	24.7 (bursting)	538.99	0.447

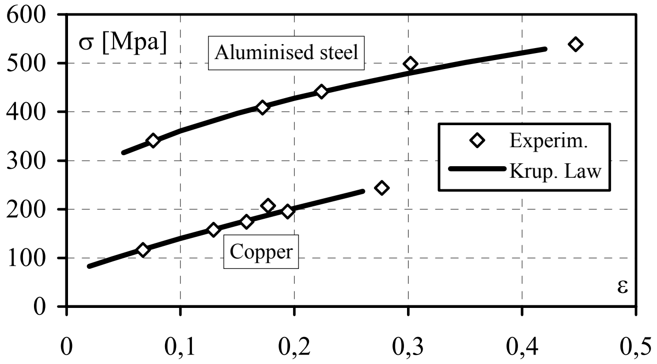

Fig. 4. Experimental data and Krupkowsky's law for copper and aluminised steel tubes.

5 CONCLUSIONS

The present paper reports the results of a study aiming at the determination of material flow stress for the simulation of THF processes. The research is based on the use of an innovative tube bulge test equipment and on an analytical model for stresses and strains calculation. In the proposed approach the tube ends are blocked and, as a consequence, in the analytical model equations based on flow rule and volume constancy were utilised to determine the tube stress state. The validity of the proposed model was tested comparing the calculated deformations with the actual ones derived from the etched grid.

The advantage of using bulge test instead of tensile test is evident in figure 5 where the obtained flow stresses are reported for the same material (an HSS steel [10]). It is clear that, during THF bulge test, the material undergoes to higher stress and strains before fracture.

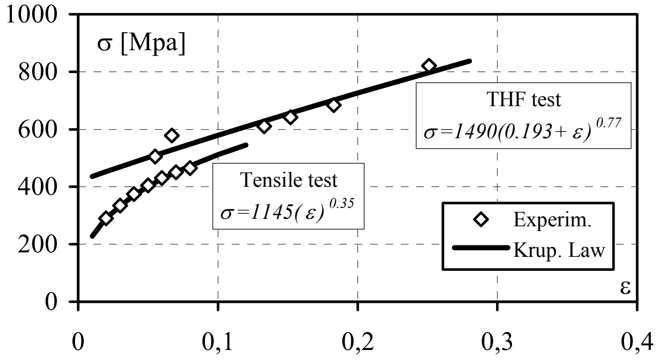

Fig. 5. Comparison between flow stress curves obtained from tensile and bulge tests for the same HSS steel tubes.

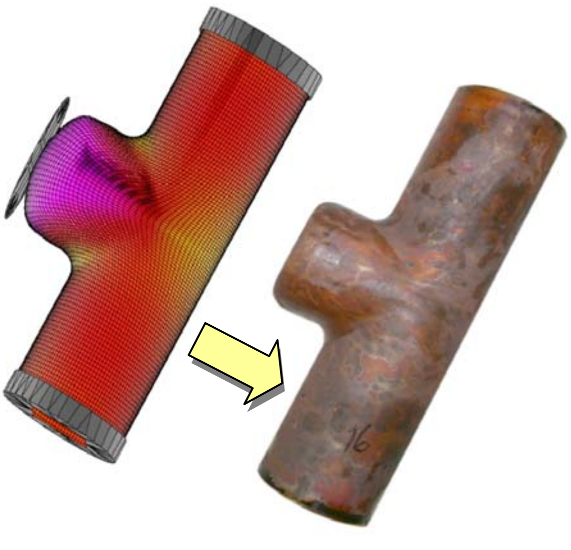

Fig. 6. Simulative and experimental results when working a T-shaped tube made of copper.

The flow stress data have been used as input in the simulation of a T-shaped copper tube. The simulative results (in terms of water pressure and axial feeding curves) utilised in the THF equipment, allowed to obtain safe parts (figure 6).

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