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GUIDELINES FOR THE DETERMINATION OF TUBE FORMING LIMITS BASED ON TENSILE, BULGE AND ELLIPTICAL TESTS

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Abstract

Tube hydroforming is a well-known technology able to manufacture complicated geometrical parts with high mechanical properties. Furthermore, the developments of new and more accurate hydraulic devices, especially high-pressure intensifiers, and the improvements achieved in control theory through computing science have made this process to become suitable for mass production in the last few years.

In this context, and due to the high dependency of tube hydroforming in the process parameters, Finite Element Analysis (FEA) has become a widely applied technique to optimise the process. Unfortunately, the accuracy of FEA results depends very much, among others, on the tube material characterisation and this one must be precisely modelled. However, very few studies have been carried out in order to develop specific tests able to obtain the tube forming limit diagrams.

The present paper describes an innovative method able to obtain the specific forming limit curves of materials further deformed by tube hydroforming processes. This method is based on non-conventional tensile tests, bulge-tests and elliptical bursting tests.

The paper also shows the approach followed for designing the tests (based on the use of numerical modelling tools), the experimental set-up as well as the results of the tests.

Key words: tube hydroforming, material characterisation, formability

1. INTRODUCTION

The trend towards the production of lightweight and cheaper parts has forced sheet metal part manufacturers to process the components not far from the limits of the material. As a result, the risk of defect occurrence has increased.

In order to be able to characterise the material and identify its limits, as precisely as possible, many different forming limit criteria have been developed in sheet metal forming technology; Forming Limit Diagrams (FLD) are very commonly applied. These diagrams have become a widely used tool for product designers and simulation analysts to optimise the design of sheet metal components, and for tooling and process engineers to develop correct dies.

The test currently used for determining the FLD of a material, the Nakazima test (Lange 1985), is suitable to characterise the material behaviour in sheet metal forming processes. Nevertheless, these conventional formability characterisation tests could not be accurate enough in order to accurately describe the material behaviour in tube hydroforming processes. The main reasons for this are: (1) the lost of formability of the sheet metal during the rolling process of the tube and (2) the fact that different stress states take place when forming a metal sheet or a metal tube.

Although tube hydroforming processes are settled down in the automotive industry, few studies have been carried out to determine its specific Forming Limit Curves (FLC), (Fuchizawa & Narazaki, 1993, Koç et al., 2001, Green, 2003). The present paper describes an innovative method to obtain the specific FLC to be used in tube hydroforming processes. This method is based on non-conventional tensile tests, bulge-tests and elliptical bursting tests.

Die shapes used in the experimentation have been optimised in a previous step using ABAQUS Explicit 6.5^{TM} numerical simulation software. The experimental study has been accomplished using DC03 mild steel (table 1) welded tubes. Diameter of the tubes is 50 mm and thickness is 1.35 mm.

***Table 1.** DC03 Steel properties.*

<table>
<tr><th colspan="4">Mechanical properties</th></tr>
<tr><td colspan="2">Tensile strength (MPa)</td><td colspan="2">390</td></tr>
<tr><td colspan="2">Yield stress (MPa)</td><td colspan="2">250</td></tr>
<tr><td colspan="2">Elongation, break (%)</td><td colspan="2">30</td></tr>
<tr><td colspan="2">Modulus of elasticity (GPa)</td><td colspan="2">205</td></tr>
<tr><td colspan="2">Poisson coefficients</td><td colspan="2">0.3</td></tr>
<tr><td colspan="2">Hollomon-Ludwick</td><td colspan="2">σ = 250+400.ε0.75</td></tr>
<tr><td colspan="2">Specific weight (g/cm3)</td><td colspan="2">7.8</td></tr>
<tr><td colspan="2">Anisotropy (0º; 45º; 90º)</td><td colspan="2">1.44; 0.95; 1.42</td></tr>
<tr><th colspan="4">Chemical properties</th></tr>
<tr><td>C 0.1 %</td><td>Mn 0.45 %</td><td>P 0.035 %</td><td>S 0.035 %</td></tr>
</table>

In order to analyse the changes with respect to conventional sheet formability tests, the developed methodology has been compared with Nakazima method and Keelers theoretical North American method used to obtain the FLC of low carbon steels.

2. TYPICAL STRAIN PATHS IN TUBE HYDROFORMING PROCESSES

Since internal pressure and axial feeding is used in tube hydroforming processes, different strain paths are achieved in the different zones of the parts as shown in figure 1.

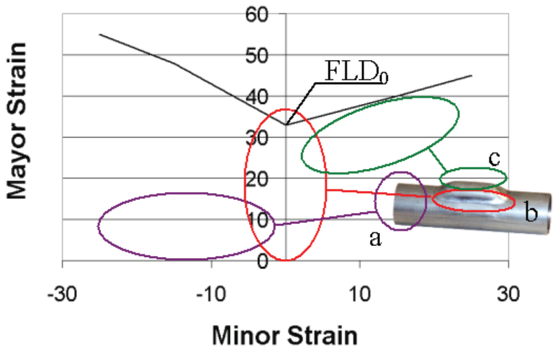

***Fig. 1.** Strain paths in guiding (a), transition (b) and expansion zones (c).*

These strain paths are different at the three different zones of a component; the guiding zones, the transition zones and the expansion zones. In the guiding zones, due to compressive forces (sealing of the tube and if necessary axial feeding), the material is compressed longitudinally (negative longitudinal strain). The circumferential strain in this zone can be considered null since the tube cannot expand. This strain path is critical because of wrinkling effects. Anyway, tube crack will not happen in this zone.

In the transition zones, the material can be compressed longitudinally (if high axial feeding is used) and circumferentially expanded. Tube crack could occur near the FLD$_0$ (centre of the FLD).

Finally, the material is deformed in plane stress in the expansion zones, being both strains longitudinal and circumferential, positive. These last zones are the most critical ones. Thickness of the tube becomes small and tube cracking can prematurely occur.

3. METHODOLOGY

3.1. Die shapes selection

Measurements of strain paths in different hydroformed parts have been done. The left side of the FLD has been proven to be not so crucial for tube hydroforming processes and cracks occur in transition and expansion zones principally. At the present study, non-conventional tensile tests of the entire tube have been used to obtain critical points in the left side of the FLD.

Free expansion until the tube crack occurs, called bulge test and shown in figure 2, has been used to obtain the central critical points of the diagram. Several studies (Koç et al., 2001, (Green, 2003, Keeler & Brazier, 1977) prove that longitudinal strain near the burst can be considered null.

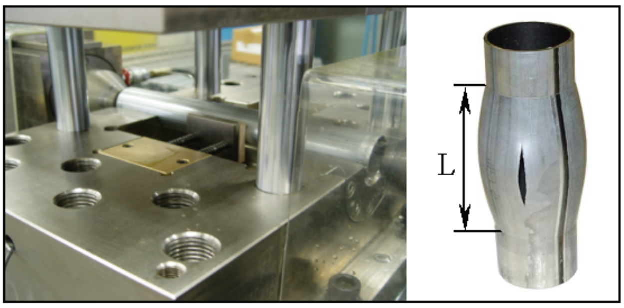

***Fig. 2.** Bulge-test die and burst tube.*

Finally, and in order to obtain the right side of the FLD where biaxial expansion of the material occurs, an elliptical die has been developed. In this way, the material is forced to expand in both directions, longitudinally and circumferentially. The design of the die is shown in figure 3.

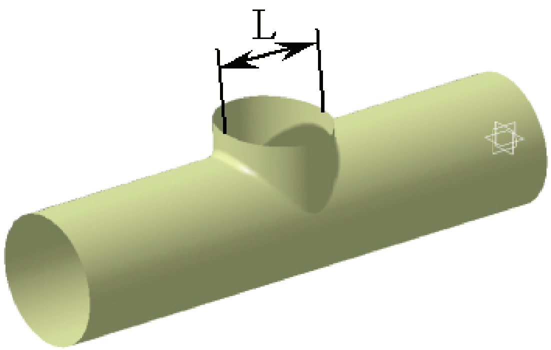

Fig. 3. Elliptical die developed to achieve biaxial expansion.

3.2. Tooling shape optimisation

Numerical simulations have been conducted using ABAQUS Explicit 6.5TM to optimise the design of the elliptical dies. The aim of the optimisation has been to find die shapes able to cover all the right side of the FLD. The variables to optimise have been the longitudinal lengths of the shapes (see L dimension in figure 2 and in figure 3). Strain path evolutions for critical elements (top of the dome) have been calculated numerically for different longitudinal lengths.

Numerical equivalent strain distribution for the different die shapes is shown in figure 4.

Figure 5 shows the different strain path trajectories for the selected final die shapes and lengths. In this way, it is possible to cover all the right side of the FLD by means of different die configurations.

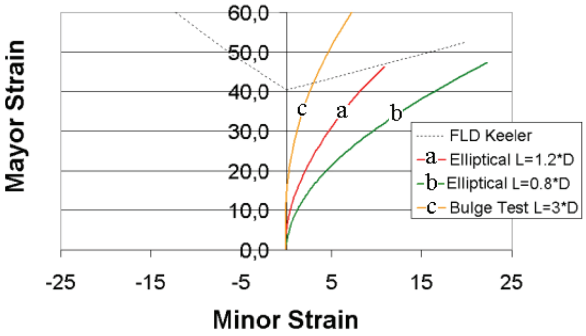

***Fig. 5.** Element strain path evolution for optimised shapes.*

4. EXPERIMENTATION

4.1. Sheet formability tests

Sheet material has been used to obtain the FLC of the raw material, using the Nakazima method. The diameter of the punch used has been 75 mm and blanks of 145 mm length and 25, 45, 60, 80, 100, 120 and 145 mm width have been tested. Nakazima die and several tested blanks are shown in figure 6.

4.2. Tube tensile tests

Entire tube tensile tests have been carried out using a hydraulic tensile machine. Material near the necking is compressed circumferentially and lengthens longitudinally. Therefore, critical points are located in the left side of the FLD. Tensile test of the tube and experimental configuration can be seen in figure 7.

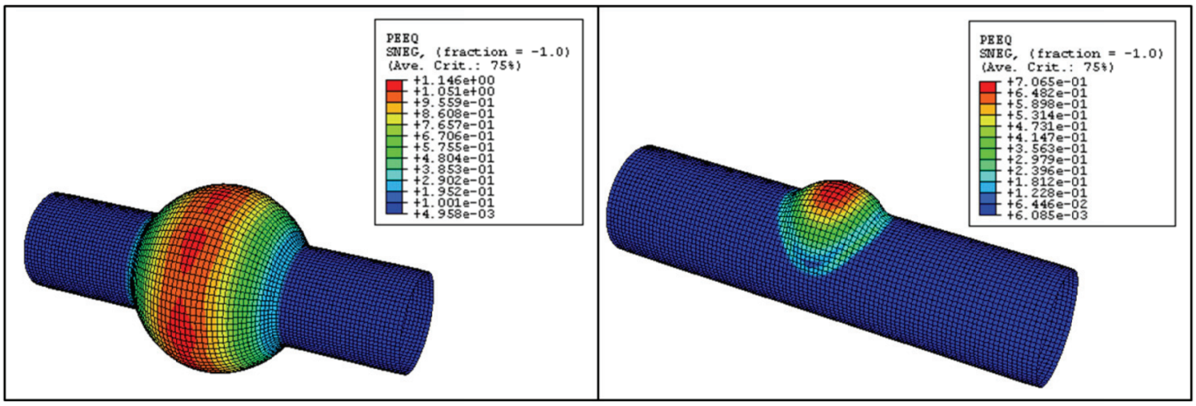

***Fig. 4.** Equivalent strain for bulge and elliptical tests.*

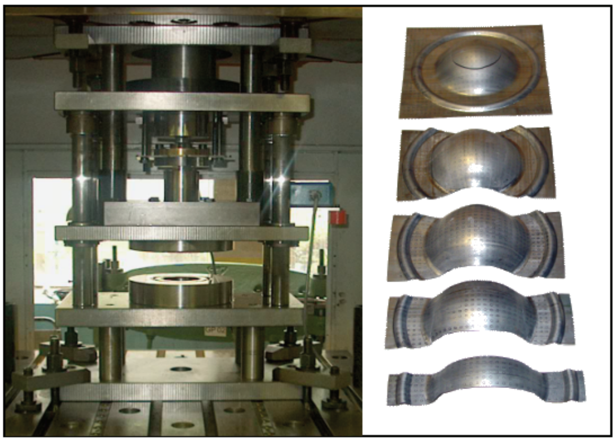

Fig. 6. Nakazima die and tested samples.

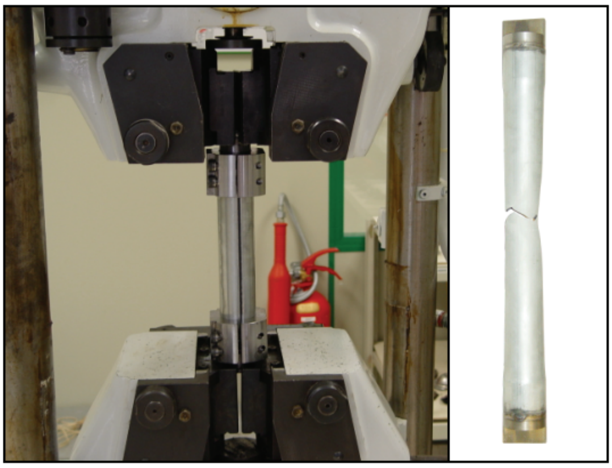

Fig. 7. Tensile test machine and stretched tube.

4.3. Bursting tests

Tubes have been burst using 0.8**D* and 1.2**D* length elliptical dies where D is the external diameter of the tested tube. Bulge-tests have been performed using 1.5**D* and 3.0**D* length dies. Elliptical burst tubes can be seen in figure 8.

Fig. 8. Elliptical burst tubes.

Pressure has been measured during the tests. Bursting pressures for the different shapes and lengths are summarised in table 2.

***Table 2.** Bursting pressures.*

Test	Internal pressure (bar)
Burst test *L* = 1.5**D* mm	210
Burst test = 3**D* mm	200
Elliptical *L* = 1.2**D* mm	265
Elliptical *L* = 0.8**D* mm	380

Die shapes with small longitudinal lengths could help to find new critical strain paths in the right side of the FLD. Internal pressure increases when bursting length becomes smaller.

5. RESULTS

PHAST® (Photogrammetric Automated Strain Testing) software has been used to analyse burst and stretched tubes deformation. Chemically etched safe and necked points have been measured in formed blanks and burst tubes.

Die shape optimisation has allowed covering the left and the right sides of the FLD accurately.

Experimental sheet and tube FLC can be seen in figure 9 and figure 10.

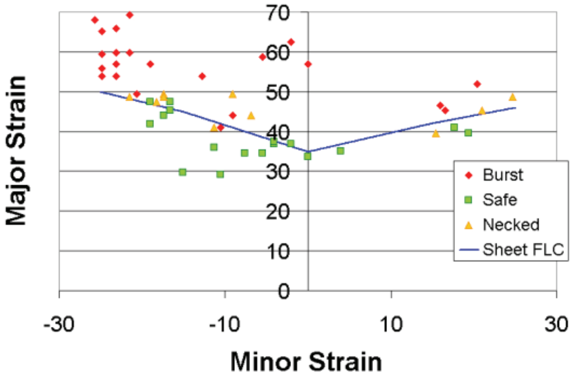

***Fig. 9.** Experimental sheet FLC.*

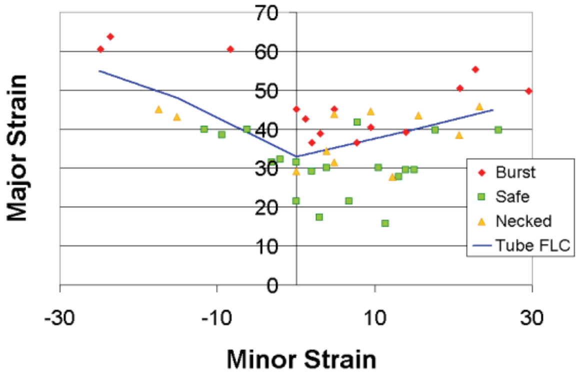

***Fig. 10.** Experimental tube FLC.*

Keeler-Brazier analytical method, which is currently used for low carbon steels (Keeler & Brazier, 1977, Goodwin, 1968, Singh, 2003), has been used to obtain the theoretical FLC.

$$FLD_0 = (23.3 + 14.13 \cdot t) \cdot (n / 0.21) \qquad (1)$$

where t is the sheet metal thickness (mm) and n is the material work hardening exponent.

For minor strain less than zero, FLC is represented by:

$$\varepsilon_\theta + \varepsilon_l = \ln(1 + FLD_0 / 100) \qquad (2)$$

where ε_θ is the minor true strain and ε_l is the major true strain.

For positive minor strains, FLC is calculated by:

$$\varepsilon_l = (FLD_0 / 100) + (0.61 \cdot \varepsilon_\theta) \qquad (3)$$

The comparison of analytical and experimental FLC can be seen in figure 11.

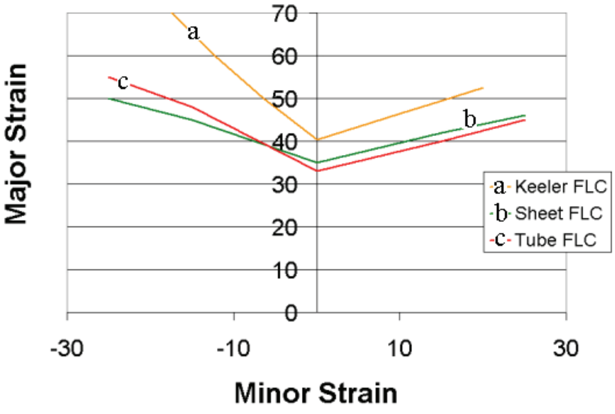

***Fig. 11.** Analytical and experimental FLC.*

6. CONCLUSIONS

A new and simple method has been developed to analyse tube material formability. This method is based on entire tube tensile tests, bulge-tests and elliptical burst tests. In parallel, sheet material formability tests have been conducted using a Nakazima die. Finally, Keeler-Brazier analytical model has been used to obtain the theoretical FLC of the material.

Results, as shown in figure 11, confirm slight differences between sheet and tube experimental curves. Therefore, sheet characterisation is supposed to be applicable in tube hydroforming processes. If bending or preforming has been used in previous hydroforming process steps, initial deformation of the tube must be taken into account when plotting strain paths in the FLD.

Keeler-Brazier analytical FLD_0 point differs with respect to experimental ones. Theoretical FLC seems to be not accurate enough for analysed material and process.

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WYTYCZNE DLA WYZNACZANIA ODKSZTAŁCALNOŚCI GRANICZNEJ RUR W OPARCIU O PRÓBY ROZCIĄGANIA I TŁOCZNOŚCI ORAZ O PRÓBĘ ELIPTYCZNĄ

Streszczenie

Hydroformowanie rur jest znaną technologią pozwalającą wytwarzać detale o skomplikowanym kształcie i wysokich własnościach wytrzymałościowych. Zaprojektowanie nowych, dokładniejszych urządzeń hydraulicznych, w szczególności wzmacniaczy wysokociśnieniowych, a także udoskonalenie sterowania procesem poprzez wspomaganie komputerowe, przyczyniły się do rozwoju procesów hydroformowania i do ich zastosowania w masowej produkcji. W tym kontekście, mając na uwadze mocną zależność przebiegu procesu hydroformowania od jego parametrów, powszechne stało się wykorzystanie metody elementów skończonych (MES) do optymalizacji parametrów procesu. Z drugiej strony, dokładność rozwiązania MES zależy bardzo mocno od prawidłowości przyjętego modelu materiału rury. Nieliczne są w literaturze badania zmierzające do opracowania próby doświadczalnej, która pozwalałaby wyznaczyć wykres odkształceń granicznych dla rur. W niniejszej pracy opisano nową metodę umożliwiającą opracowanie krzywych odkształcalności granicznej w procesie hydroformowania.

Metoda ta opiera się na niekonwencjonalnej próbie rozciągania, próbie tłoczności i eliptycznej próbie pękania. W artykule pokazano również podejście wykorzystujące numeryczne modelowanie do zaprojektowania doświadczenia oraz do interpretacji wyników prób.

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