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On the Utilization of Circle Grid Analysis in Thin-walled Forming of Tubes: Experimental and Numerical Evaluation

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Abstract

This paper presents an investigation on different tube forming processes by plastic deformation, including expansion, reduction and inversion of tube ends, using circle grid analysis in order to obtain strain-loading paths in different regions of the principal strain space. The experimental work was carried out on commercial AA6063-T6 tubes and includes independent material characterization by means of tensile, stack compression and instability tests. Finite element modelling of the tube forming processes by means of an in-house computer program gives support to the presentation and allows assessing the overall accuracy, validity and reliability of using circle grid analysis to investigate formability and failure in tube forming.

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Keywords: Tube forming; circle grid analysis, experimentation; finite element modelling

1. Introduction

Strain analysis carried out in the principal strain space by means of circle grid analysis is an important and well-established methodology to evaluate formability in metal forming [1, 2]. In contrast to sheet and bulk metal forming [3], the utilization of circle grid analysis to investigate formability and failure in tube forming has not been properly addressed in the literature until a recently work published by the authors [4] aimed at characterizing plastic strains in
thin-walled tube expansion. In fact, to author’s knowledge, there are no systematic investigations in the field prior to Centeno et al. [4], apart from the previous attempt to characterize the formability limits of thin-walled tubes performed by Alves et al. [5], who made use of circle grid analysis to study the occurrence of failure by wrinkling in the nosing of thin-walled tubes using an hemispherical shaped die.

This paper extends the work on tube expansion [4] to other tube end forming processes such as reduction and inversion in order to obtain strain-loading paths in different regions of the principal strain space. With this purpose, numerical and experimental work made use of AA6063-T6 commercial tubes. Material characterization was carried out by means of tensile, stack compression and instability tests, whereas finite element modelling of tube forming was performed using the in-house computer program I-form. Results allow assessing the overall accuracy, validity and reliability of using circle grid analysis to investigate formability and failure in tube forming.

2. Experimentation

This section presents the mechanical characterization of the tube material, provides information on the methods that were utilized to determine experimental strains in the principal strain space and on the plan of experiments that was carried out for the selected tube-end forming processes.

2.1. Mechanical characterization of the material

The investigation was performed on commercial AA6063-T6 aluminium tubes and its stress-strain curve was determined by means of tensile and stack compression tests carried out at room temperature. The tensile test specimens were cut out from the supplied tubes by electro discharge machining and the stack compression test specimens were assembled by piling up circular discs machined out from the supplied tubes. The tests were performed at room temperature on a hydraulic testing machine (Instron SATEC 1200 kN) with a cross-head speed equal to 5 mm/min. Table 1 provides a summary of the mechanical properties of the AA6063-T6 aluminium tubes. The resulting stress-strain curve can be found in [4].

The critical instability force for the occurrence of axisymmetric local buckling was determined by compressing tubular specimens with 70 mm initial length and free-ended boundary constraints between flat parallel platens. The critical instability force obtained is 48.5 kN (further details are explained in [4]).

Table 1. Mechanical properties of the AA6063-T6 tubes

<table>
<thead>
<tr>
<th>Modulus of elasticity (GPa)</th>
<th>Yield strength (MPa)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Elongation at break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>68.0</td>
<td>216.5</td>
<td>236.3</td>
<td>12.8</td>
</tr>
</tbody>
</table>

2.2. Strain measurement procedure

The outer surface of the tubes was electrochemically etched with a grid of circles of 2.5 mm initial diameter. The strain loading paths were constructed from the meridional and circumferential in-plane strains ($\varepsilon_\phi$, $\varepsilon_\theta$) at the grid circles as follows:

$$
\varepsilon_\phi = \ln\left(\frac{b}{d}\right) \quad \varepsilon_\theta = \ln\left(\frac{a}{d}\right)
$$

where $a$ and $b$ (Fig. 4a) are the lengths of the major and minor axes of the ellipses that resulted from plastic deformation of the original grid of circles with an initial diameter $d$.

In the cases that tube forming leads to fracture, the utilization of circle grids to obtain the in-plane strains provides values that cannot be considered as the fracture strains. Moreover, such grids create measurement difficulties and are sensitive to the initial size of the circles owing to inhomogeneous deformation in the neighbourhood of the crack. In such cases, the procedure for determining the fracture strains required measuring the tube wall thickness before and after fracture at several locations along the crack in order to obtain the ‘gauge length’ strains. The measurements were
performed in samples taken from the fractured regions with a Stereomicroscope Nikon SMZ800 with ×20 magnification and analysed using KAPPA Image Base Metreo 2.7.2. The analysis of the cracks allowed concluding if failure by fracture occurred with or without previous necking. This helped understanding the conditions upon which necking does, or does not, precede failure by fracture in thin-walled tube forming.

2.3. Plan of experiments

Tubular specimens with a reference radius $r_0$ of 20 mm, an initial thickness $t_0$ of 2 mm and an initial length $l_0$ of 70 mm were utilized for all the experimental work. The plan of experiments presented in Table 2 was set up in order to investigate the validity and reliability of using circle grid analysis to investigate formability in elementary tube end-forming expansion, reduction and inversion.

<table>
<thead>
<tr>
<th>Case</th>
<th>Semi-angle of inclination $\alpha$ (degrees)</th>
<th>Punch radius, $r_p$ (mm)</th>
<th>Die radius, $r_d$ (mm)</th>
<th>Fillet radius of the die, $r_{df}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion</td>
<td>15º / 30º / 45º</td>
<td>28 / 49 / 28</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reduction</td>
<td>17º</td>
<td>-</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>Inversion</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5</td>
</tr>
</tbody>
</table>

The experiments were performed in a hydraulic testing machine (Instron SATEC 1200 kN) under a constant displacement rate of 5 mm/min. The desired shape of the tubes was achieved by forcing dedicated punches or dies, with different geometries (Fig. 1), into the tube end. The lubricant used was disulphide molybdenum (MoS2) grease.

3. Finite Element Modelling

The numerical simulation of the tube end-forming processes was performed with the finite element computer program I-form. The program was developed by the authors and is built upon the irreducible finite element flow formulation that is based on the following variational principle (extended to account frictional effects). Information on the computer implementation of the finite element flow formulation can be found elsewhere [6].
The punches and dies were modelled as rigid objects and discretized by means of contact-friction linear elements. The tubes were modelled as deformable objects and discretized by means of linear quadrilateral elements, taking advantage of rotational symmetry (Fig. 2). The choice of solid elements instead of membrane or shell elements was based on a previous work of the authors [7] in which quadrilateral elements with four elements in the wall thickness were successfully utilized for modelling the force-displacement evolution and the distribution of the major field variables taking into account bending effects at the punch entry.

![Finite element modelling the expansion of thin-walled tubes at the initial and final instants of deformation for (a) expansion, (b) reduction and (c) inversion](image)

Fig. 2. Finite element modelling the expansion of thin-walled tubes at the initial and final instants of deformation for (a) expansion, (b) reduction and (c) inversion

The lower half of the tubes have a higher mesh density than the upper half allowing a more accurate comparison between the numerical predicted and the experimentally measured strains along the surfaces of the tubes. In connection to this, it is worth mentioning that the finite element predicted distribution of strains along the $r, \theta, z$ cylindrical coordinates global axis needed to be transformed into the $t, \theta, \phi$ local axis (corresponding $\theta, \phi$ with the meridional and circumferential directions respectively, along which the experimental strains are measured on the outer surface of the tube using circle grid analysis) in order to ensure appropriate comparison with the experimental strains determined by circle grid analysis. The transformation of the strain tensor was performed as follows,

$$
E_{t,\theta,\phi} = T^T E_{r,\theta,\phi} T
$$

where $T$ is the matrix corresponding to a local rotation about the $\theta$-axis. The angle of rotation was defined locally in order to match the inclination of each element along the outer tube surface.

To conclude, it is worth mentioning that the overall central processing unit (CPU) time for a typical analysis shown in Fig. 2 was approximately 5 min on a laptop using one Intel i7-6500U CPU (2.60 GHz) processor.

4. Results and discussion

Fig. 3 shows the experimental and finite element predicted evolutions of the force vs. displacement for the expansion ($15\text{\textdegree}$), reduction and inversion test cases. As seen, the overall agreement is good, allowing validation to proceed into the experimental and numerical prediction of the principal strains.
Regarding the principal strains, Fig. 4 presents a schematic representation of the circle grid on the initial tube and after de forming process for the case of expansion (Fig. 4a) and the numerically predicted strain loading path versus the experimental results corresponding to the point A (Fig. 4b). As seen, fracture occurs at the tube end, close to this point A represented in Fig. 4a and inserted pictures in Fig. 4b.

On the other hand, Fig. 5 depicts the numerical prediction of circumferential versus meridional strains for reduction (Fig. 5a) and inversion (Fig. 5b) and the corresponding experimental values obtained by circle grid analysis. The experimental strains in expansion and inversion were evaluated at point ‘A’ (Fig. 4a) for the various intermediate stages of the vertical displacement of the upper (compression) die considered, whereas the strains for the case of reduction were measured at the end of the reduction process due to the impossibility to remove the specimen from the die in intermediate forming stages.
Analyzing the experimental and numerical values of the circumferential $\varepsilon_{\theta}$ and meridional $\varepsilon_{\phi}$ strains plotted in Fig. 4 and Fig. 5 it can be conclude that: (i) the expansion strain path is near linear with a slope close to pure tension, (ii) the reduction strain path is located in the 3rd and 4th quadrant of the principal strain space, in which circumferential strains $\varepsilon_{\theta}$ are negative (Fig. 5a) and may lead to compressive instability by local buckling and formation of wrinkles and (iii) the external inversion strain path starts as pure compression and changes into plane strain as the tube end inversion reaches 90° with respect to tube axis (refer to the dotted line in Fig. 5b, not experimentally assessed). The overall agreement between numerical predictions and experimental values is once again good.

5. Conclusions

This paper is a second contribution towards the objective of characterizing the formability limits and fracture of thin-walled tubes by combination of finite elements and circle grid analysis. For this purpose, three different tube-end forming processes (expansion, reduction and inversion) were selected and their strain loading paths evaluated for different tube locations. Results are promising and the next objective of the authors is the identification of other tube end forming processes that will be able to provide strain paths in regions of the principal strain space that are still not covered by the selected tube end-forming processes that were presented in this paper.

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References