Introduction

Tube end forming processes are commonly utilized for producing of a wide variety of shapes and profiles such as inversions, flares, expansions, reductions, beads and noses by means of single or multiple forming operations.
Aims and scope

(i) Fabrication of metallic liners for aerospace composite overwrapped pressure vessels (COPV’s)

(ii) Attachment of tubes to other tubes or sheets for air-pressure lines, liquid pipes, exhaust systems and lightweight structures, among other applications.

Introduction

Motivation

Disadvantages of conventional manufacturing processes for producing COPV liners:

(i) Labour intensive

(ii) Time consuming

(iii) Environmental problems due to considerable wasting of raw materials

(A COPV liner with 330 mm diameter is machined from a block weighting 240 kg to obtain a thin-shell liner weighting 6 kg!)

(iv) Requires significant and costly inspection welding procedures before overwrapping.

There is room for reducing the total price of COPV’s for aerospace applications.

For example:
The cost of a liner with 330 mm diameter (70 litters) can be reduced to approximately 1/3 (from the actual 45 k€ to roughly 15 k€ per unit) by replacing conventional manufacturing processes by tube forming.
Fabrication of metallic liners

Tooling system
Schematic representation of the open, closed and extraction positions

Fabrication of metallic liners

Tooling system
Detail showing the main components of the tool system, the upper sharp edge die, the preform and the final liner after removing by internal recyclable mandrel by melting (below 200°C).
Fabrication of metallic liners

Finite element modelling

Utilization of in-house finite element modelling capabilities:
(i) Electro-thermo-mechanical computer program based on the finite element flow formulation
(ii) Parallel iterative solver with pre-conditioning by means of incomplete gauss factorization
(iii) Isotropic and anisotropic constitutive laws
(iv) Damaged modelling based on uncoupled or coupled porous plasticity approaches
(v) Contact with friction between deformable bodies
(vi) All-Hexahedral and all-quadrilateral non-structured meshing of work material with enhanced octree based refinement procedures
(vii) Discretization of the active tool parts by means of contact-linear rigid spatial triangles or elastic deformable solid elements

Material characterization

Tensile, compression and stack compression tests
Fabrication of metallic liners

Process development

Experimentation and finite element modelling allowed developing the internal recyclable mandrels for avoiding collapse by local buckling and wrinkling.

Fabrication of metallic liners

Process development

Experimentation and finite element modelling also allowed defining the outside deburring of the tube ends, the clearance between the tube and liner (tooling) and the shape of the internal recyclable mandrel.
Fabrication of metallic liners

Process development
Thickening around the polar opening of the reservoirs is advantageous for assembling the gas outlet and blind end ports.

Technology transfer
ESA (ARTES 5.2) - Innovative manufacturing technology for producing metallic liners for COPV’s aerospace applications
International Patent: EP 2 265 396 B1

Fabrication of metallic liners

2006 2012 2014 2015+
40 mm 120 mm 200 mm 330 mm
Joining of tubes

Motivation
Disadvantages of conventional tube attachment processes:
(i) Labour intensive
(ii) Environmental constraints
(iii) Limited by industry standards or by aesthetics due to the utilization of fasteners
(iv) Requires costly inspection procedures whenever welding or brazing are used
(v) Requires the utilization of fixing systems to minimize distortions arising from the heating and cooling cycles associated with welding
(vi) Requires surface preparation and time consuming procedures if adhesives are used
(vii) Difficulties in ensuring good assemblies in inclined tube-tube or tube-sheet applications

Joining of tubes

Commercial and custom solutions
(i) Commercial solutions - Tee fittings, saddle adapters and weld-o-lets for standard geometries and materials
(ii) Custom solutions - Nozzle-weld and spin-forming
(iii) Custom solutions - Mechanical fixing with fasteners (nuts and bolts or rivets), welding, and structural adhesive bonding
Joining by forming of tubes

Commercial and custom solutions

State-of-the-art reviews by Mori et al. (2013) and Groche et al. (2014) provide excellent overviews on the existing and potential applications of joining by forming.

<table>
<thead>
<tr>
<th></th>
<th>Joining by forming</th>
<th>Joining by welding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanism</strong></td>
<td>Plastic deformation</td>
<td>Melting with addition of filler materials</td>
</tr>
<tr>
<td><strong>Shape of the connections</strong></td>
<td>Arbitrary geometries</td>
<td>Limited to butt, lap, corner and edge joints</td>
</tr>
<tr>
<td><strong>Operating temperature</strong></td>
<td>Ambient</td>
<td>Melting point</td>
</tr>
<tr>
<td><strong>Heat-affected zones</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Shielding gases</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td>Metals and polymers</td>
<td>Metals (similar)</td>
</tr>
<tr>
<td><strong>Coated materials</strong></td>
<td>Possible</td>
<td>Very difficult or impossible</td>
</tr>
<tr>
<td><strong>Energy consumption</strong></td>
<td>Less</td>
<td>More</td>
</tr>
<tr>
<td><strong>Productivity</strong></td>
<td>More</td>
<td>Less</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Less</td>
<td>More</td>
</tr>
<tr>
<td><strong>Environmental friendliness</strong></td>
<td>More</td>
<td>Less</td>
</tr>
</tbody>
</table>

Joining by forming successfully combines the growing demands for high productivity, low fabrication costs and environmental friendliness with high performance and material versatility.

Innovative solutions

The aims and scope is to provide solutions and guidelines to extend the current technology offer for connecting tubes and fixing tubes to sheets.
Joining by forming of tubes

Mechanical characterization (S460MC carbon steel tube)

Tensile and stack compression tests

Axial compression of tubes between flat parallel platens with different constraint ended conditions

Joining by forming of tubes

Inclined tube connections

The new proposed solution is based on controlling the development and propagation of plastic instability waves in thin walled tubes subjected to axial compression beyond the bifurcation point of the load-displacement curve.
Joining by forming of tubes

Process development

Finite element modelling allowed understanding the deformation mechanics associated with triggering and propagation of the inclined, out-of-plane, plastic instability waves that are needed for the production of inclined tube connections.
Joining by forming of tubes

Process development

Experimentation confirmed that deformation modes are dependent on the slenderness ratio $l_{gap}/r_0$ and on the inclination angle of the dies, among other parameters.

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>1</td>
</tr>
<tr>
<td>60°</td>
<td>1</td>
</tr>
<tr>
<td>12°</td>
<td>2</td>
</tr>
<tr>
<td>90°</td>
<td>2</td>
</tr>
</tbody>
</table>

When the slenderness ratio $l_{gap}/r_0$ is very large deformation mode 3 not only produces two asymmetric instability waves that interfere destructively with each other, as the second instability wave often results incomplete due to absence of free gap opening between the upper and lower dies at the end of stroke.
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Joining by forming of tubes

Process development

The utilization of internal mandrels is mandatory in order to ensure triggering and propagation of the sound plastic instability waves (with outward dominant plastic flow) that are needed to produce the inclined tube attachments.
Joining by forming of tubes

Process development

Load-displacement evolutions allow understanding the development of plastic instability waves.

Finite element modelling allowed modelling the deformation mechanics the inclined tube joints.
Joining by forming of tubes

Other examples

End-to-end connection of tubes

The idea behind the end-to-end connection of tubes is based on a sequence of three different tube forming processes that are carried out sequentially in a single stroke: (i) expansion, (ii) local buckling and (iii) clamping by mechanical locking.
Process development

Joining by forming of tubes

Finite element modelling allowed understanding the deformation mechanics associated with the expansion, local buckling and clamping by mechanical locking that are needed for the production of end-to-end tube connections.

Experimental and finite element predicted cross sections allowed concluding that the leftmost test sample does not ensure locking between the two tubes whereas the rightmost test sample presents a joint with two compression beads instead of one.
Joining by forming of tubes

**Process development**

Assessment of the overall performance by means of destructive testing:
(a) tension, (b) torsion, (c) bending and (d) water tightness.

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**Joining by forming of tubes**

**Process development**

Experimental and finite element modelling allowed extending the new joining process to thermoplastic tubes made from polyvinylchloride (PVC), polyethylene (PE) and polypropylene (PP).
Joining by forming of tubes

Process development

... and also to the connection of tubes made from dissimilar materials

The grips (purple and grey colours) are split in two halves and can be hydraulically actuated for locking and compression. The dies (black colour) are also split in two halves for allowing the two joined tubes to be easily removed.

Joining by forming of tubes

Process development

In case of dissimilar materials with very different strengths there is a need to employ a two-stage variant of the previously described process.
Joining by forming of tubes

Process development

Finite element modelling and experimentation allowed developing sound PVC-S460MC joints by identification of tube slenderness ratio $l_{gap}/r_0$ as a critical process parameter.

The joints can withstand pressures well above the maximum operating pressure of the PVC tubes (10 bar).
Joining by forming of tubes to sheets

Tube-sheet connections

The same deformation mechanism was utilized in the following industrial application retrieved from the bottom seat frame of a passenger car.

Inclined tube-sheet connections

And the same deformation mechanisms can also be applied to produce inclined tube-sheet connections.
Joining by forming of tubes to sheets

Inclined tube-sheet connections

Extension to materials with very different strengths may sometimes lead to difficulties. In this case there are difficulties of the PVC sheet to withstand the local pressure of the compression beads without being pushed and bent away from the tube when the amount of non-symmetric plastic flow caused by the slenderness ratio is significant.

Joining by forming of tubes to sheets

Tube-sheet connections

Potential applications can be found almost elsewhere and can easily make use of dissimilar materials (e.g. polymers and metals)
Conclusions

The first part of the presentation was focused on an innovative tube forming process that is capable of shaping commercial tubular preforms into seamless liners in a single stroke while meeting the specific requirements of aerospace industry concerning storage capacity, shape of the domes and connection to gas feeding systems.

The second part of the presentation was focused on new, cost-effective and environmentally friendly processes for connecting tubes and tubes to sheets that are built upon plastic instability of thin-walled tubes.

The selected examples demonstrate the potential of combining the fundamental modes of deformation of tube end forming for developing new exciting tube forming and joining processes.

Acknowledgment

I would like to pay a special tribute to the personal qualities and scientific generosity of Professor Niels Bay who, back in the early 90’s, when he was already a well-known leading international researcher, accepted to collaborate and support a junior Portuguese assistant professor with very little to offer in return.

From the early 90’s up to today, I had the privilege of working for long periods in Denmark with Professor Niels Bay and co-workers. DTU became my second home and as a result of this we co-authored 61 publications (26 research papers in international journals).

Moreover, Professor Niels Bay’s role in the scientific advisory committee of our research group in Portugal helped my co-workers and I to consolidate our vision in manufacturing and to establish our laboratory infra-structure at the University of Lisbon.

I am deeply honoured and happy of being here today.