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RESEARCH ARTICLE

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Innovative cold joining technologies based on tube forming

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Abstract – This paper is focused on innovative cold joining technologies for connecting tubes and fixing tubes to sheets. The proposed technologies are based on the utilization of plastic instability waves in thin-walled tubes subjected to axial compression and may be seen as an alternative to conventional joining technologies based on mechanical fixing with fasteners, welding and structural adhesive bonding. Besides allowing connecting dissimilar materials and being successfully employed in fixture conditions that are difficult and costly to achieve by means of conventional joining the new proposed technologies also cope with the growing concerns on the demand, lifecycle and recycling of materials.

Key words: Joining, Cold forming, Tubes, Experimentation, Finite element modelling

1. Introduction

Modern lightweight structures employed in architecture, engineering and building construction make use of tubular trusses in which tubes are connected to each other or fixed to sheets. Tubular joints are also essential elements in air-conditioning, refrigeration, heat-exchangers, supply lines and pipelines to convey fluids from one location to another.

In case of connecting tubes, there are several well-known types of joints based on commercially available tee fittings, saddle adapters and weld-o-lets for standard geometries and materials, such as carbon steel, stainless steel, copper and polyethylene, among other thermoplastics (Figures 1a–1c).

The main advantage of connecting tubes by means of commercially available tee joints is that it is a cost effective solution whenever the quantity of connections to be performed is significant. However, the utilization of these types of joints is limited by industry standards and always requires cutting and preparation of tube ends, welding or brazing and, in most cases, quality inspection of the welds.

Custom based solutions are generally based on the utilization of on nozzle-weld and spin-formed joints (Figures 1d and 1e). Nozzle-weld joints (Figure 1d) require cutting a hole in the main tube, shaping a contoured end in the branch tube to match the diameter of the main tube and welding along the contour. Spin-formed joints (Figure 1e) also requires cutting a hole in the main tube but the difference is that material around that hole is subsequently shaped into a tee fitting where the branch tube will be brazed or welded.

In case of fixing tubes to sheets, the most widespread technologies are based on the utilization of fasteners (nuts and bolts or rivets), welding and structural adhesive bonding (Figures 1g–1i). The majority of these joints are simple to design and easy to assemble and disassemble but their range of application is often limited by various technical constraints.

For example, mechanical couplings based on fasteners are limited by the maximum loading capacity that nuts, bolts and rivets can support safely.

Welding joints suffer from dimensional inaccuracies and heat-affected zones resulting from the heat-cooling cycles, from difficulties of welding dissimilar materials (e.g., joining steel or aluminium tubes to aluminium or copper sheets), from the production of undesirable fumes and smokes in fabrication, and from expensive and time consuming routes related to the above mentioned quality inspection procedures.

Structural adhesive bonding requires careful surface preparation with tight tolerances and is accomplished by placing a thin film of liquid or semisolid adhesives between the counterfacing surfaces of the tubes and sheets to be joined. The procedure needs time for the adhesive to cure and the resulting joints may experience decrease in performance over time under adverse environmental conditions.

From what was mentioned before, it can be concluded that no matter the application and the differences between the technologies that are currently available for connecting tubes (Figures 1a–1e) and fixing tubes to sheets (Figures 1g–1i), their universe of application is always limited by aesthetic, physical, chemical, and mechanical requirements.

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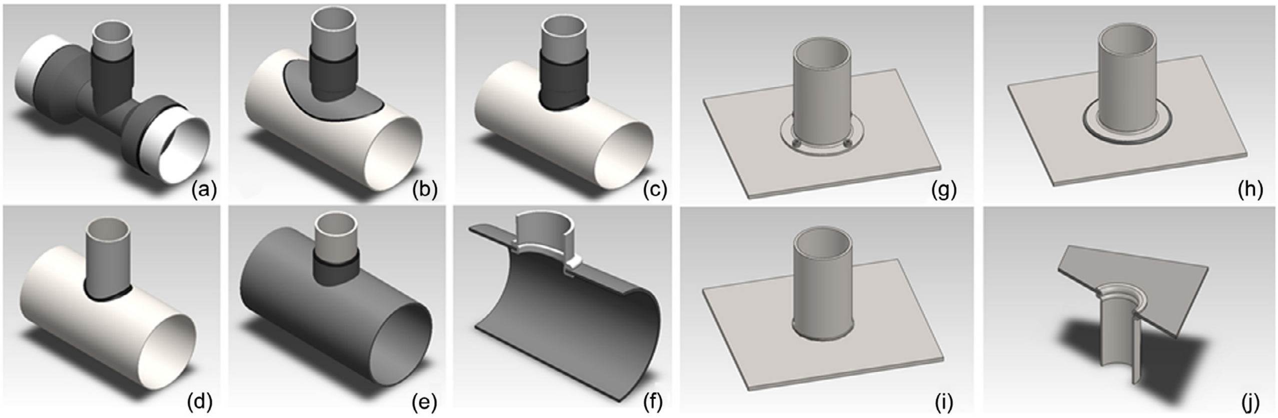

Figure 1. Conventional and new proposed technologies for connecting tubes and fixing tubes to sheets.

Table 1. Summary of the main features of joining by forming and by welding.

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

Recent developments in joining by forming that are comprehensively systematized in the state-of-the-art reviews by Mori et al. [1] and Groche et al. [2] allow concluding that plastic deformation offers great potential to connect tubes and to fix tubes to sheets. Moreover, joining by forming combines the growing demands for high productivity, low fabrication costs and environmental friendliness with high performance and material versatility. Table 1 summarizes the main differences between joining by forming and by welding.

This paper is built upon recent developments in joining by forming and presents innovative technologies that make use of axisymmetric or asymmetric plastic instability waves in thin-walled tubes subjected to axial compression for connecting tubes and fixing tubes to sheet panels at room temperature in situations where the axis of the branch tube or sheet is perpendicular or inclined to the axis of the main body tube. In case of connecting tubes by cold forming, the paper will also be focus on recent developments in the joining of tubes by their ends.

This paper aggregates several new technologies of joining by forming that were recently developed and published by the authors [3, 5]. These technologies are not only capable of connecting tubes and fixing tubes to sheets made from dissimilar materials (e.g. metals and polymers) as they can be successfully employed in fixture conditions that are difficult and costly to achieve by means of conventional joining technologies.

Figures 1f and 1j present schematic examples of the application of the new proposed technologies for cases in which the axis of the branch tube or sheet is perpendicular to the axis of the main body tube that will be comprehensively described in the presentation.

2. New joining technologies

2.1. Inclined connections

The new proposed technologies for connecting tubes [3] and fixing tubes to sheets [4] are schematically shown in Figure 2. The idea behind the technologies 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.

In case of tube joining (Figure 2a) the left and middle schematic drawings show the upper and lower dies that are needed to trigger and propagate inclined, out-of-plane, instability waves between contoured dies at the open and closed positions. The rightmost schematic drawing shows an application of this

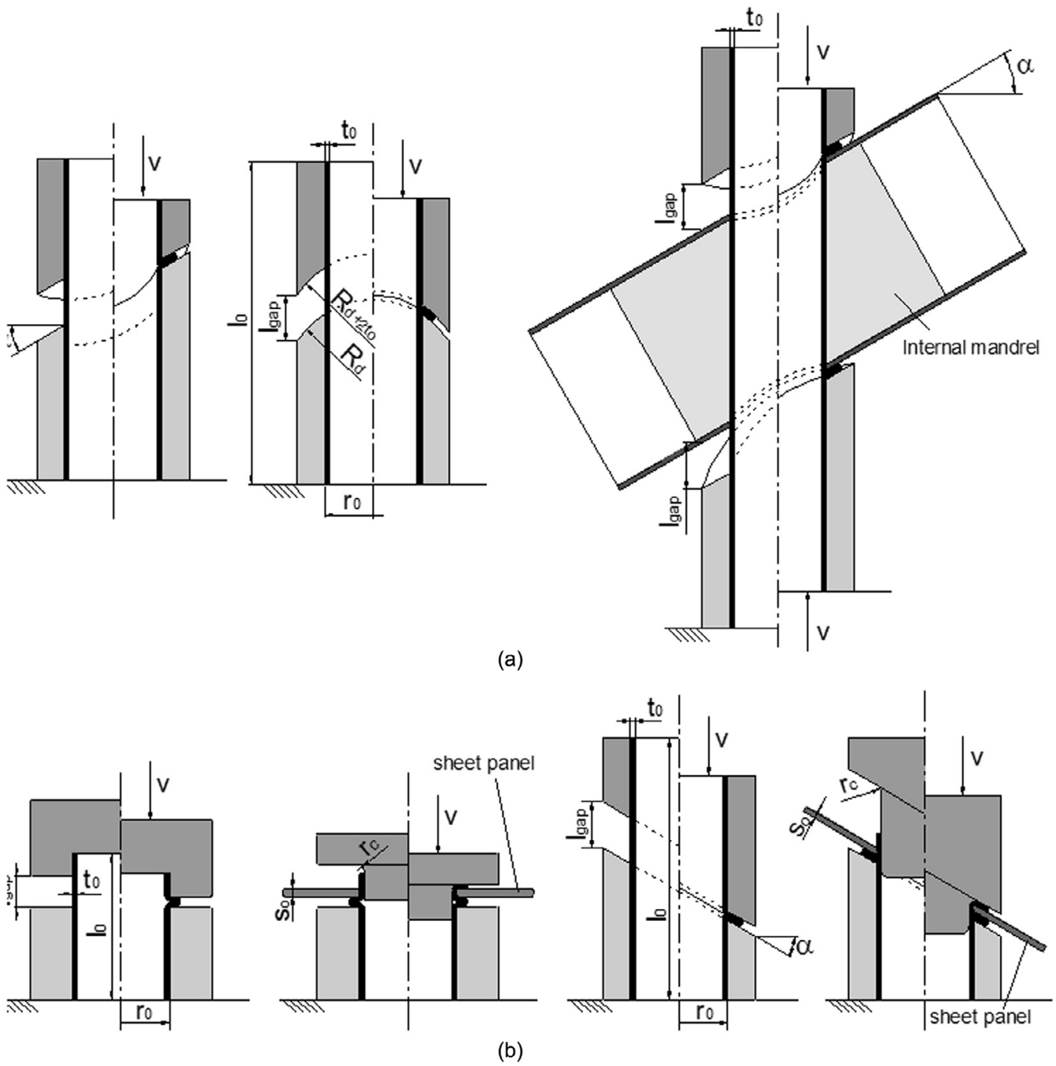

Figure 2. (a) Sectional schematic views of the tool system to develop and propagate inclined, out-of-plane, instability waves in tubes and to produce inclined tube joints. (b) Sectional schematic views of the tool system to develop and propagate inclined, in-plane, instability waves to fix tubes to sheets.

concept for producing inclined tube joints. The sectional views show the active tool components consisting of the upper and lower contoured dies and the internal mandrels (if present). The internal diameter of the dies is dedicated to a specific reference radius r_0 of the main body tube. The radius R_d of the parting out-of-plane surface of the dies together with its inclination α to the axis of the main body tube are dedicated to a specific instability wave or, in case of tube joining, to a specific radius of the branch tube. The difference between the radius R_{d+2t_0} and R_d of the upper and lower parting surfaces is crucial to accommodate the plastic compression bead at the end of stroke. The initial gap opening l_{gap} between the upper and the lower contoured dies controls triggering and propagation of the plastic instability waves namely, the number, width and relative position of the compression beads along the axis of the main tube.

Figure 2b shows two different tool systems utilized for fixing tubes to sheets that also make use of axisymmetric (leftmost setup) or asymmetric (rightmost setup), in-plane, plastic instability waves. The joints are accomplished by compression beading and axisymmetric or asymmetric tube end flaring. The plastic instability waves are produced in appropriate flat or contoured dies whereas flaring is accomplished by compressing the upper tube end with and appropriate radiused punch in order to expand material outwards and to form a single-lap inclined flange.

In connection to what was said above, the main operating parameters that are considered relevant to the new technologies for connecting tubes and fixing tubes to sheets are: (i) the slenderness ratio l_{gap}/r_0 between the initial gap opening and the outer radius of the tube, (ii) the ratio t_0/r_0 between the wall thickness and the outer radius of the tube, (iii) the mandrel (if present) and (iv) the tribological conditions.

Other relevant operating parameters that are process dependent are: (i) the inclination angle α of the contoured dies, (ii) the radius r_c of the flaring punch and (iii) the angle β of the tube end chamfers.

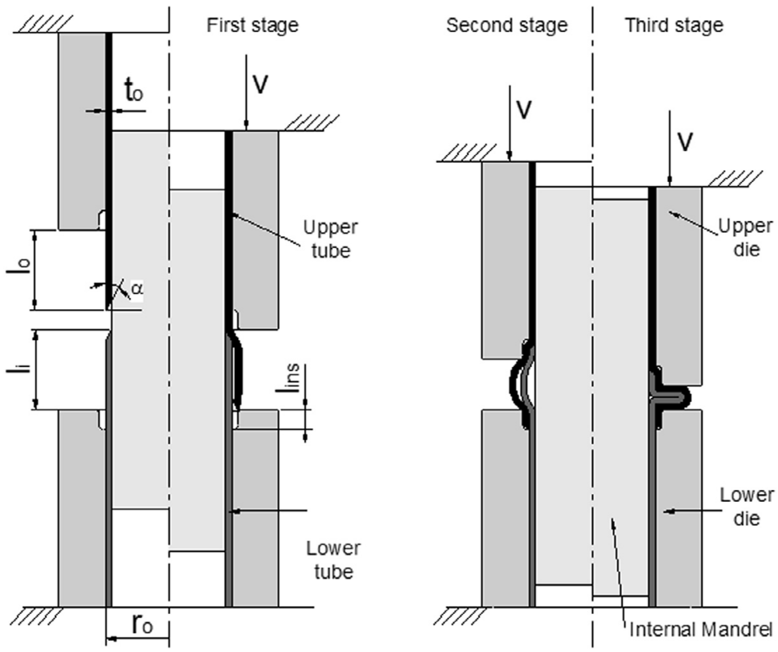

Figure 3. Sectional schematic views of the tool system to connect two tubes by their ends.

2.2. End-to-end connections

The new proposed technology for joining two tubes by their ends [5] is schematically shown in Figure 3. As seen from the open, intermediate and closed positions of the tool system, joining is accomplished by a sequence of three different cold forming stages that are carried out sequentially in a single stroke: (i) expansion, (ii) local buckling and (iii) clamping by mechanical locking.

Expansion is performed by forcing the upper tube against the chamfered end of the lower tube in order to enlarge the unsupported height l_0 of the upper tube radially and to create adjacent counterfacing surfaces between the two tubes to be joined. During this stage the chamfered end of the lower tube acts like a tapered punch (refer to "first stage" in Figure 3).

Once the unsupported height l_0 of the upper tube reaches the end of the depth of insertion l_{ins} resulting from the radial clearance between the tube and the upper end of the lower die, there is a sudden change in material flow and plastic instability waves are triggered as a result of local bucking under axial compression loading (refer to "second stage" in Figure 3). The internal mandrel ensures that the plastic instability waves are formed exclusively outwardly so that design specifications of the inner diameter of the tube joint are met and alterations in the flow of liquids or gases are prevented.

Finally, propagation of the plastic instability waves under continuous axial compression loading clamps the adjacent counterfacing surfaces of the two tubes by mechanical locking (refer to "third stage" in Figure 3). It is worth noting that although the new proposed joining process has been developed for carbon steel tubes it can also be used in tubes made from other metals or thermoplastics such as polyethylene (PE) and polypropylene (PP) [6].

The main operating parameters of this technology are similar to those listed in Section 2.1 but it is worth noticing that $l_{gap} \cong l_0 + l_i + 2l_{sc}$ in case of joining tubes by their ends and that the depth of the side clearance l_{sc} that controls the insertion of the tubes in the lower and upper dies also plays a role in the process.

3. Experimentation

3.1. Mechanical characterization of the materials

The experimental development of the new proposed technologies were performed on commercial S460MC (carbon steel) welded tubes and commercial PVC-U PN10 (unplasticized polyvinylchloride). The S460MC tubes were supplied with an outer radius $r_0 = 16$ mm and a wall thickness $t_0 = 1.5$ mm, and were utilized in the "as-received" condition. The PVC-U PN10 tubes were supplied with an outer radius $r_0 = 16$ mm and a wall thickness $t_0 = 1.6$ mm, and were manufactured in compliance with EN 1452-2 standard for a maximum operating pressure of 10 bar.

The stress-strain curve of the S460MC tubes was determined by combining tensile and stack compression tests carried out at room temperature on a hydraulic testing machine (Instron SATEC 1200 kN). In contrast, the strength differential effect of PVC requires determination of the individual stress-strain curves for tension and compression by means of tensile and stack compression tests (Figure 4a).

The tensile test specimens were machined from the supplied tube stock in accordance to the ASTM D 638 (PVC-U) and ASTM E8/E8M–09 (S460MC) standards. The stack compression test specimens consisted of multi-layer cylinders that were assembled by pilling up 3 circular discs with 12 mm

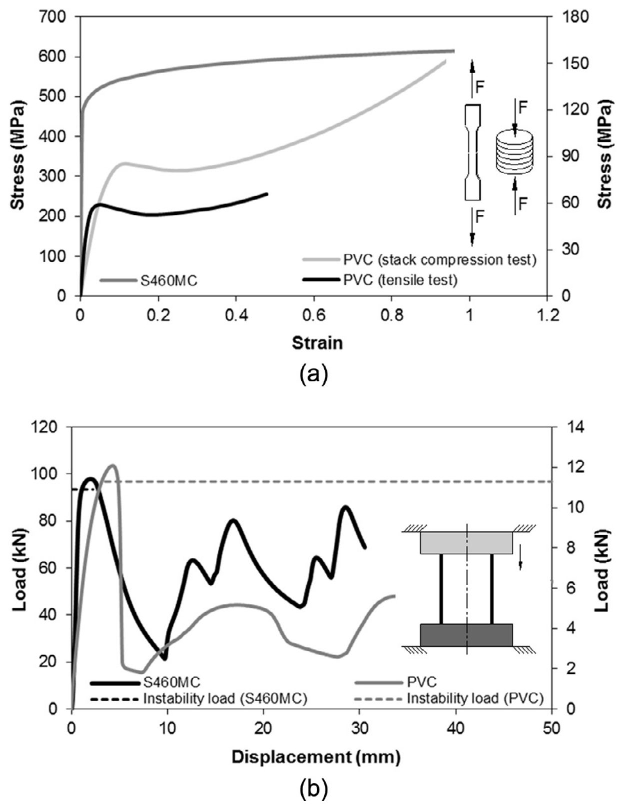

Figure 4. Mechanical characterization of the commercial S460MC and PVC tubes. (a) Stress-strain curves and (b) load-displacement curves and critical instability loads for the axial compression of tubes between flat parallel platens. The differences in strength of both materials justify the existence of two vertical axes in both plots. S460MC carbon steel refers to the left vertical axis while PVC refers to the right vertical axis.

diameter and 1.6 mm (PVC) or 1.5 mm (S460MC) thickness cut out from the supplied tubes by a hole-saw. All the tests were carried out at room temperature on a hydraulic testing machine (Instron SATEC 1200 kN) with a cross-head speed equal to 10 mm/min.

The critical instability load for the occurrence of local buckling was determined by compressing PVC and S460MC steel tubes with 100 mm initial length between flat parallel platens. As seen in Figure 4b, the shape of the experimental load-displacement curves that were obtained for the tubular specimens of each material are similar but the absolute values of their critical instability loads F_{cr} are very different. In fact, the critical instability load of S460MC carbon steel tubes is 93.5 kN while that of PVC is 11.3 kN.

3.2. Testing conditions

The experimental setups associated to the different joining technologies that are schematically shown in Figures 2 and 3 were installed in the hydraulic testing machine (Instron SATEC 1200 kN) where the mechanical characterization of the tubes had previously been performed. The experiments were carried out at room temperature with a cross head speed equal to that utilized in the mechanical characterization of the tube materials with the purpose of identifying the modes of deformation and setting up the process feasibility window of the new joining technologies as a function of a selected number of operating parameters. The influence of some of these parameters will be provided later in Section 5.

4. Numerical modelling

Because the experimental development of the new joining technologies for connecting tubes and fixing tubes to sheets was performed with a quasi-static constant displacement rate of the upper-table of the hydraulic testing machine, no inertial effects on plastic deformation are likely to occur and therefore no dynamic effects in the joining process are needed to be considered. These operating conditions allowed numerical modelling to be performed with the finite element flow formulation and enabled the authors to utilize their in-house computer program I-form that has been extensively validated against experimental measurements of metal forming processes since the end of the 1980's [7].

I-form is based on the finite element flow formulation and includes an extension to pressure-sensitive polymers that allows modelling metal and polymer tubes simultaneously. The extension of the flow formulation to pressure-sensitive polymers is based on the utilization of a non-associated flow rule in which the plastic potential $Q = J_2$ commonly utilized in metallic materials is not retrieved from the yield function $F(\sigma_{ij})$ that explicitly accounts for the strength-differential effect resulting from the differences between tensile σ_T and compressive σ_c flow stresses [8],

$$F\left(\sigma_{ij}\right) = \bar{\sigma}^2 - \sigma_C \cdot \sigma_T + \left(\sigma_C - \sigma_T\right)\sigma_{kk} = 0, \qquad (1)$$

where $\bar{\sigma} = \sqrt{\frac{3}{2}\sigma'_{ij}\sigma'_{ij}}$ is the effective stress and $\sigma_{kk} = \delta_{ij}\,\sigma_{ij}$.

The non-associated flow rule where $Q = J_2$ and $\dot{\lambda}$ is a scalar factor of proportionality is given by,

$$\dot{\varepsilon}_{ij}^p = \dot{\lambda}\frac{\partial Q\left(\sigma_{ij}\right)}{\partial \sigma_{ij}}. \qquad (2)$$

The finite element flow formulation giving support to I-form is built upon the following extended variational statement that accounts for contact with friction between rigid and deformable objects:

$$\Pi = \int_V \bar{\sigma}\,\dot{\bar{\varepsilon}}\,\mathrm{d}V + \frac{1}{2}K\int_V \dot{\varepsilon}_v^2\,\mathrm{d}V - \int_{S_T} T_i u_i\,\mathrm{d}S + \int_{S_f}\left(\int_0^{|u_r|}\tau_f\,\mathrm{d}u_r\right)\mathrm{d}S, \qquad (3)$$

where, $\dot{\bar{\varepsilon}}$ is the effective strain rate, $\dot{\varepsilon}_v$ is the volumetric strain rate, K is a large positive constant enforcing the incompressibility constraint of both metals and polymers and V is the control volume limited by the surfaces S_U and S_T, where velocity and traction are prescribed. Friction at the contact interfaces S_f is treated as a traction boundary condition and the additional power consumption term is modelled through the utilization of the law of constant friction $\tau_f = mk$.

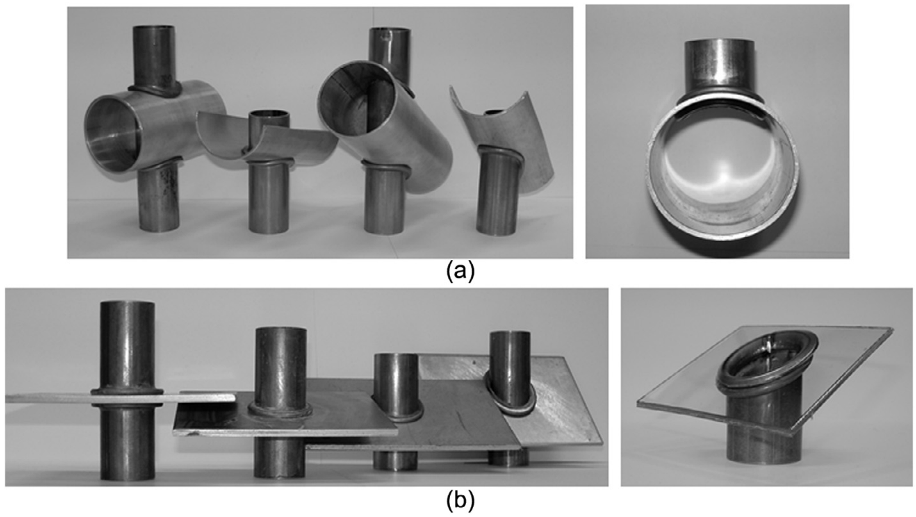

Figure 5. Application of the new proposed technology for (a) connecting full-size and half-sectioned tubes and for (b) fixing tubes to sheets (metallic and polymeric) at different inclination angles.

The contact between deformable bodies (e.g. between the counterfacing surfaces of the tubes or between the tubes and sheets, among others) was modelled by means of a non-linear procedure based on a penalty approach. The procedure is comprehensively described by Nielsen et al. [9] and has the advantage of avoiding additional degrees of freedom as in case of alternative solutions based on the utilization of Lagrange multipliers.

The tubes and sheets were discretized by means of 2D and 3D finite element models as a function of the rotational symmetry conditions of the joining operation. In case of rotational symmetry, the cross section of the tubes and sheets was discretized by means of quadrilateral elements across the thickness. In the absence of rotational symmetry, the discretization is fully three-dimensional and performed by means of hexahedral elements. The dies and mandrels were treated as rigid bodies.

5. Results and discussion

5.1. Inclined connections

Figure 5a shows applications of the proposed technology for connecting tubes (or half-tubes) in situations where the axis of the branch tube is perpendicular or inclined to the axis of the main body tube. Figure 5b shows applications for fixing tubes to sheets in situations where the axis of the sheet is perpendicular or inclined to the axis of the main body tube. The solutions can, for example, be successfully employed in the seat bottom frame of automotives as an alternative to welding in order to reduce costs and eliminate heat distortion problems. All the connections shown in Figure 5 were performed between welded carbon S460MC steel tubes, seamless aluminium AA6062 tubes, aluminium AA5754 sheets and polycarbonate sheets.

Figure 6 shows the results obtained from the numerical modelling of inclined connections. As seen, Figure 6a presents the initial, intermediate and final predicted geometry of a tube attachment where the axis of the branch tube (labelled as "Tube B") is inclined by 30° to the axis of the main body tube (labelled as "Tube A"). Joining is performed by means of two inclined, out-of-plane, plastic instability waves that closely match the intersection of the two tubes. Two different types of mandrels are employed; (i) a conventional internal mandrel placed inside the main body tube ("Mandrel A") and (ii) a special purpose internal sectioned mandrel made of two different parts ("Mandrel B") placed inside the branch tube. The conventional mandrel avoids the development of unacceptable inward plastic flow during triggering and propagation of the plastic instability waves whereas the special purposed sectioned mandrel (allowing for the easy removal of mandrel in practice) prevents the compression beads to plough into the branch tube. The branch tube behaves as a sleeve during the entire joining process and its internal sectioned mandrel contributes decisively to ensure the overall success of the inclined joining process.

Figure 6b, allows understanding the role played by the internal mandrel in preventing the development of plastic instability waves exhibiting both inward and outward plastic flow during the fixing of tubes to sheets in situations where the axis of the sheet is perpendicular or inclined to the axis of the main body tube (refer also to Figure 5b). The compression beads resulting from these plastic instability waves exhibiting both inward and outward plastic flow would lead to non-acceptable joints and, therefore, justify the reason why the utilization of internal mandrels is mandatory in order to ensure the overall quality and tolerances that are required for the tube-sheet inclined connections.

5.2. End-to-end connections

Figure 7a shows a photograph of several tube specimens that were connected by their ends using the new proposed technology. The observation of the real and finite element predicted

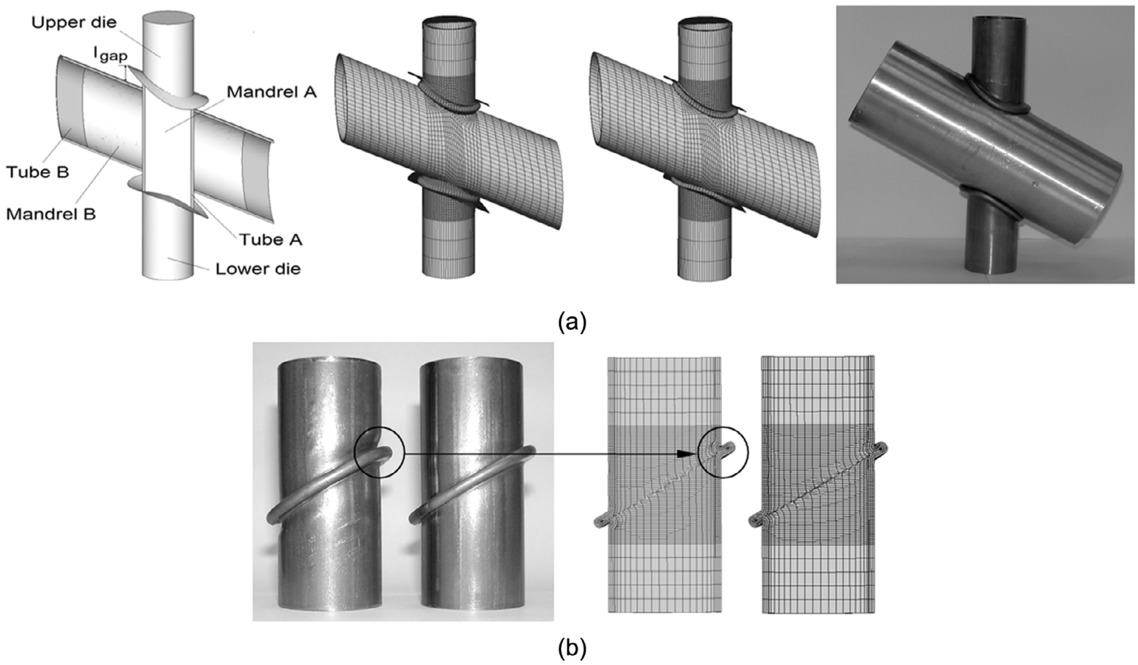

Figure 6. (a) Finite element model and predicted geometries at the middle and end of stroke with photograph of an inclined connection ($\alpha = 30°$) between the two tubes. (b) Photograph and finite element predicted geometries disclosing the influence of the internal mandrel in the development of sound asymmetric, in-plane, plastic instability waves for fixing tubes to sheets.

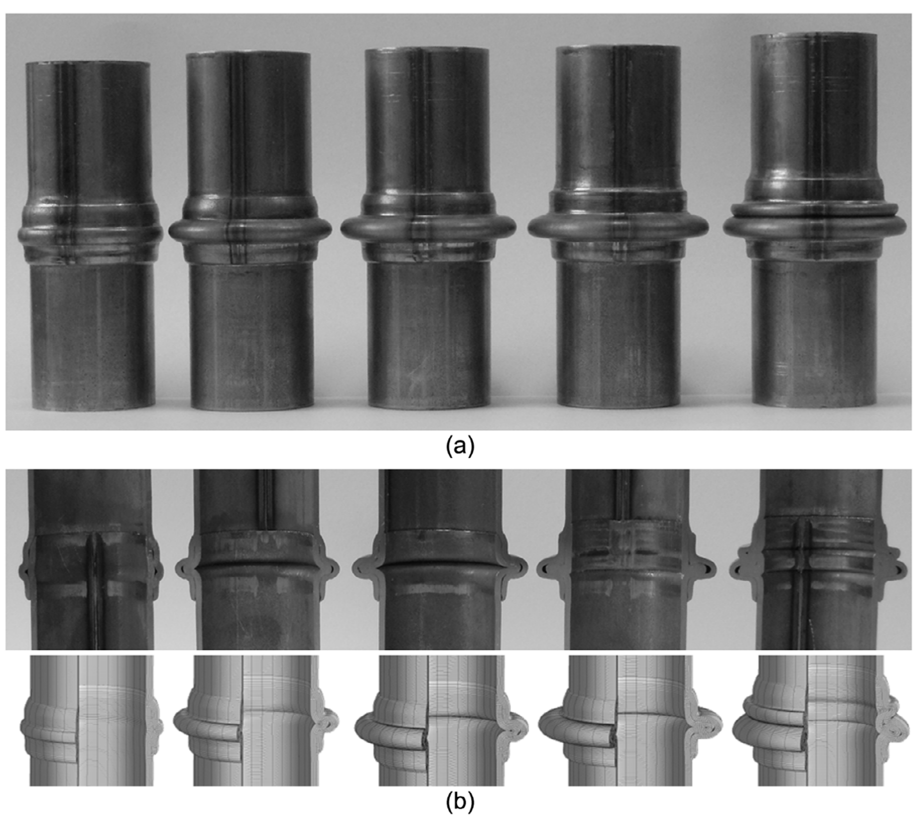

Figure 7. Modes of deformation associated to end-to-end joining of S460MC tubes by cold forming. (a) Experimental joints and (b) experimental and finite element predicted geometries of the cross sections for specimens with different values of the slenderness ratio l_{gap}/r_0.

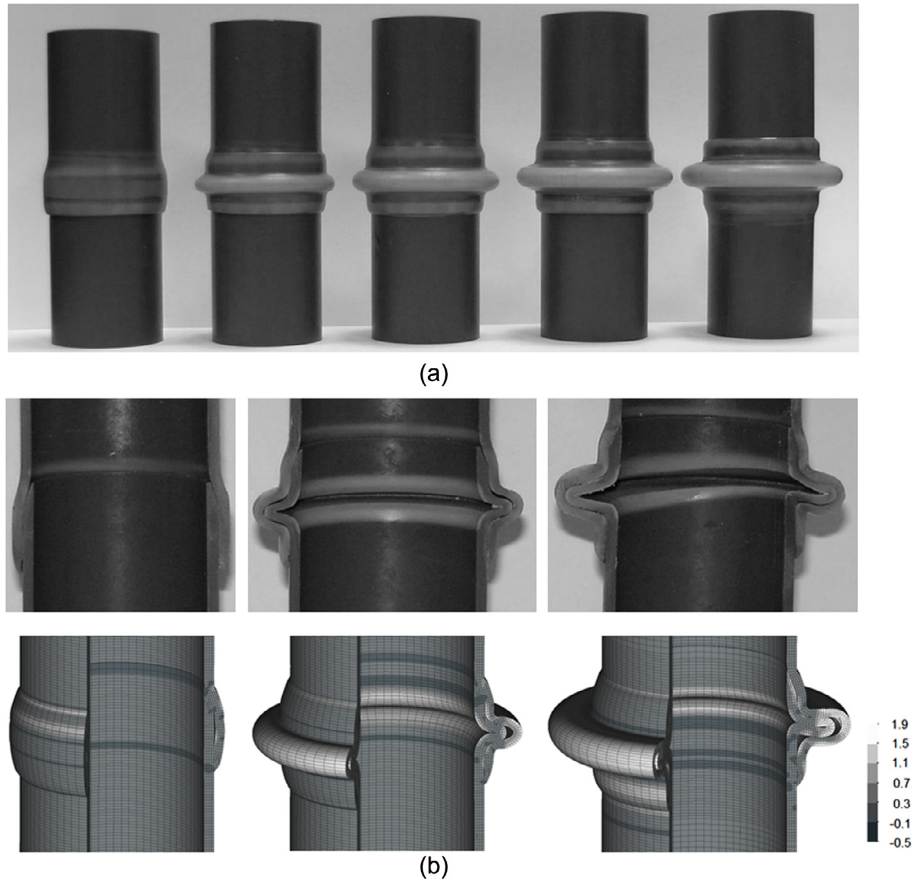

Figure 8. Modes of deformation associated to end-to-end joining of PVC tubes by cold forming. (a) Experimental joints and (b) experimental and finite element predicted geometries of the cross sections for specimens with different values of the slenderness ratio l_{gap}/r_0.

cross sections in Figure 7b allows concluding that the leftmost test sample (corresponding to $l_{gap}/r_0 = 1.9$) does not ensure locking between the two tubes whereas the rightmost test sample (corresponding to $l_{gap}/r_0 = 4.4$) presents a joint with two compressions beads instead of one.

In case of the leftmost test sample, the absence of connection is because the initial unsupported gap height l_{gap} is not big enough to allow compression beads to develop and lock with each other by plastic instability. In case of the rightmost test sample, the formation of two compression beads instead of one is due to the fact that high values of the initial unsupported gap height l_{gap} provide conditions for the development of multiple compression beads that will interfere and be placed on top of each other, as they are formed in-between the upper and lower dies.

Neither the operative conditions corresponding to the leftmost test sample nor those corresponding to the rightmost test sample are acceptable for connecting the two tubes by their ends. The process window is therefore restricted to values of the slenderness ratio l_{gap}/r_0 in the range between the two abovementioned limits. However, it is worth noting that the process window must not be confused with the potential range of applicability because the limits on the slenderness ratio l_{gap}/r_0 only define the range of values of the unsupported heights of the upper and lower tubes that need to be utilized for successfully connecting any two tubes by their ends.

Figure 8 shows the application of the proposed technology to the connection of two PVC tubes by their ends. Similarly to what authors observed in metallic tubes, the end-to-end joining of PVC tubes by cold forming is dependent upon the development and propagation of sound axisymmetric plastic waves at the gap opening l_{gap} between the upper and lower dies.

When the slenderness ratio l_{gap}/r_0 has a value smaller than the minimum threshold it is not possible to connect the PVC tubes by their ends because the initial gap opening l_{gap} is not big enough to allow plastic instability waves to develop and clamp the two tubes by mechanical locking (refer to the leftmost sample of Figure 8a, where $l_{gap}/r_0 = 0.56$. In contrast, when the slenderness ratio l_{gap}/r_0 has a value larger than the maximum threshold it is not possible to ensure a sound and reliable connection of the PVC tubes by their ends (refer to the rightmost sample in Figure 8a where $l_{gap}/r_0 = 3.75$). Values of the slenderness ratio l_{gap}/r_0 in-between the leftmost and rightmost samples in Figure 8a are acceptable for connecting the two PVC tubes by their ends by means of cold forming. The process window is therefore characterized by values of the slenderness ratio l_{gap}/r_0 in the range between 1.8 and 3.2.

The observation of the different modes of deformation in the end-to-end joining of PVC tubes by their ends adds a new physical phenomenon known as "stress whitening" that does not occur in metallic tubes (Figure 8b). Stress whitening consists in the change of color with plastic deformation and is attributed to the occurrence of crazing in the regions of the PVC tubes subjected to high values of tensile stresses. This phenomenon is particularly important in PVC and Figure 8b includes the finite element predicted distribution of crazing in accordance with the normalized version of Bucknall's modification of the stress-bias criterion due to Sternstein and Ongchin [10].

6. Conclusions

The new proposed technologies for connecting tubes and tubes to sheets by triggering and controlling the propagation of plastic instability waves in thin-walled tubes offer several advantages as compared with conventional technologies based on mechanical fixing with fasteners, welding or structural adhesive bonding because they are:

- flexible solutions capable of handling small, medium or large batch sizes with different geometries and high levels of repeatability in production line;
- environmentally friendly solutions that allow savings in raw material and eliminate filler materials and shielding gases;
- energy saving solutions that eliminate heat-cooling cycles as well as heat affected zones in the regions of the tubes and sheet panels that are joined together;
- value added solutions that are capable of connecting tubes and fixing tubes to sheet panels made of dissimilar materials;
- cost-efficient solutions that require low amount of capital investment because they can be designed to operate with existing machine-tools.

Because the new proposed technologies can be successfully employed in fixture conditions that are difficult and costly to achieve by means of conventional technologies they can also be utilized to foster innovative ideas in product development.

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