Joining of Tubes to Sheets by Sheet Bulk Forming

Experimental and numerical analysis

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Abstract. Fixing tubes to sheets at room temperature without the need of adding material is fundamental for the evolution of the way we can join different components, because as we know almost every single component results from the joining of two different components.
The new proposed process of joining by forming for fixing tubes to sheets at room temperature takes place in two stages. The first stage involves the production of an annular flange by partial compression of the tube wall thickness along the longitudinal direction and the second and last stage consists in the upsetting of the free tube end against a sheet with a bevelled hole in order to lock the two parts together. This dissertation combines experimentation and finite element modelling and uses different arrangements of process variables for characterizing typical failures and defects, for understanding the mechanics of material pile-up and for determining the overall force requirements. Also included in this dissertation is an analytical model for designing the joints and the validation of the overall joining concept by means of finite element modelling and experimentation. Destructive pull-out test demonstrates the effectiveness of the new proposed joining process.

Introduction

Tube-sheet connections are used across a wide range of engineering applications. The automotive industry provides several good examples in critical safety parts such as the connection of the right-hand to the left-hand side panels of seat-back frames and the connection between the lever and the fulcrum of handbrake systems. Other examples can be found in heat exchangers and in lightweight frame structures, namely, in the assembly of staircases, roofs and floors made from sheet metal panels.

There are three main technologies for joining tubes to sheets: welding, adhesive bonding and mechanical fastening or riveting. Welding (Fig. 1) is the fastest conventional joining process but its utilization is limited by distortion and residual stresses arising from the expansion and contraction of the weld and adjacent base metals during the heating-cooling cycles. Clamps, jigs and fixtures that lock and hold the tubes and sheets in position during welding are commonly used to eliminate (or partially eliminate) distortion. Other reasons for not welding are the difficulty in joining dissimilar materials and the cost and time of the inspection of defects that is more significant than with any other technology.

Adhesive bonding (Fig. 1) circumvents the above mentioned difficulties in joining dissimilar materials but its utilization is limited by environmental working conditions related to service temperature and moisture, among others. In this case, the use of clamps, jigs and fixtures is also needed to ensure a uniform pressure across the adhesive bonded area during curing time.

Mechanical fastening and riveting (Fig. 1) is the simplest and cheapest available technology for producing non-permanent (fastened) or permanent (riveted) tube-sheet connections. The fastened and riveted joints can be used with dissimilar materials and are free from thermal after effects and curing time requirements. They can also be easily assembled and disassembled without damaging the sheets. However, the utilization of fasteners and rivets is limited by the maximum load they can safely support, by aesthetic requirements and by working conditions in corrosive environments.

Joining by forming (Mori et al., 2014) was firstly applied to connect tubes to sheets at room temperature by Alves et al. (2011) (Fig. 1). The process is based on the combination of compression beading and tube inversion, requires no additional filler materials and accessories, and avoids the problems of forces being concentrated at the points of fastening or riveting. However, the resulting tube-sheet connections may show cracks in the plastically deformed beds in case of materials with low fracture toughness and may also experience loosening during impact or repeated loading and unloading.

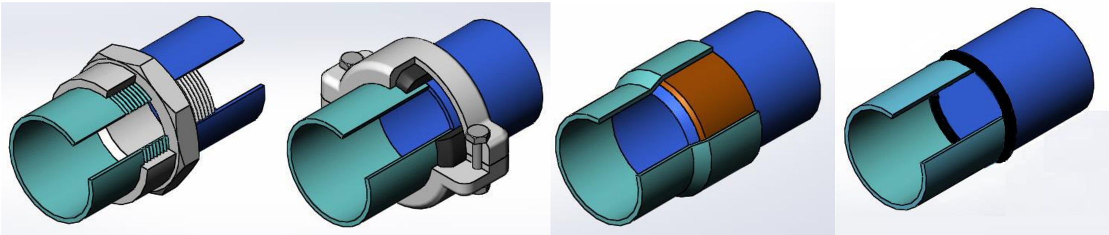


Fig. 1. Tube-sheet connections produced by mechanical fastening or riveting, adhesive bonding and welding.

In order to overcome the above mentioned problems arising from the integrity and reliability of the compression beads produced by local plastic instability, Alves et al. (2017)(a) recently proposed the utilization of sheet-bulk forming (Merklein et al., 2012) and upsetting to produce tube-sheet connections (Fig. 2). The sheet-bulk forming of tubes involves partial compression of the tube wall thickness in order to pile-up material along its axial (longitudinal) direction and produce a localized annular flange with rectangular cross section and tight dimensional control (Fig. 2a). The upsetting of the free tube end against a sheet with a bevelled hole ensures the mechanical interlocking of the tube to the sheet by means of a flat joint without protrusion of the tube end above the sheet surface (Fig. 2b).

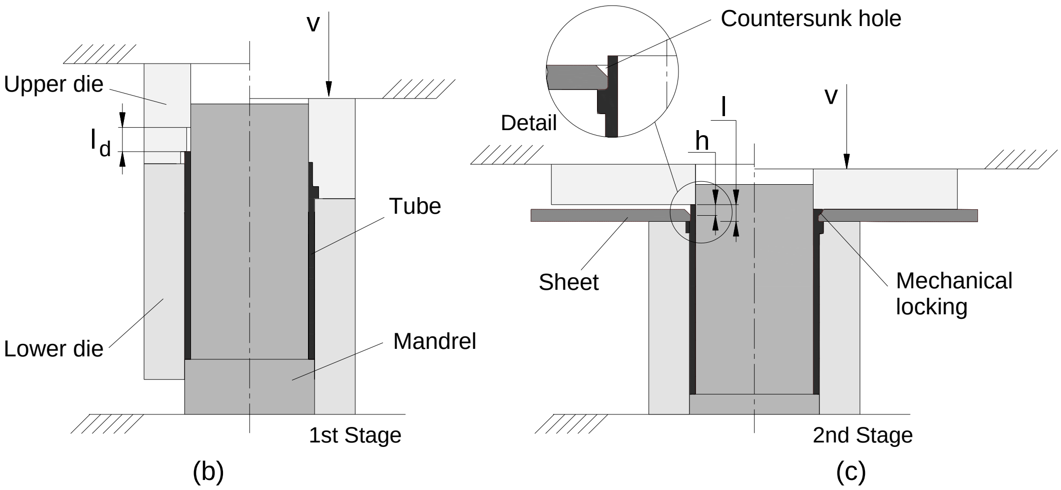


Fig. 2. Joining tubes to sheets with bevelled holes by sheet-bulk forming (Alves et al., 2017(a)).
(a) Schematic representation of the tool to perform the sheet-bulk forming of tubes (first stage of the process);
(b) Schematic representation of the tool to perform the mechanical interlocking by upsetting of the tube end against the bevelled hole of the sheet (second stage of the process).

The aims and objective of this dissertation is to study the overall mechanics of the tube-sheet connections produced by sheet-bulk forming. This variant of the joining of tubes to sheets by sheet-bulk forming is performed at room temperature and allows tubes and sheets to be made from dissimilar materials. The resulting joints are easy to disassemble and recycle at the end of the product lifecycle.

Process Variables and Analytical Framework

Fig. 3a presents a schematic detail of the tube and of the bevelled sheet hole immediately after placing the sheet upon the annular flange produced by partial sheet-bulk forming of the tube wall thickness along its axial direction (refer to Fig. 2a). The major process variables are shown in the figure and comprise the free height h and the wall thickness t of the tube end, the inner radius r_0 of the tube, the sheet thickness t_s and the side length a of the triangular cross section of the bevelled sheet hole.

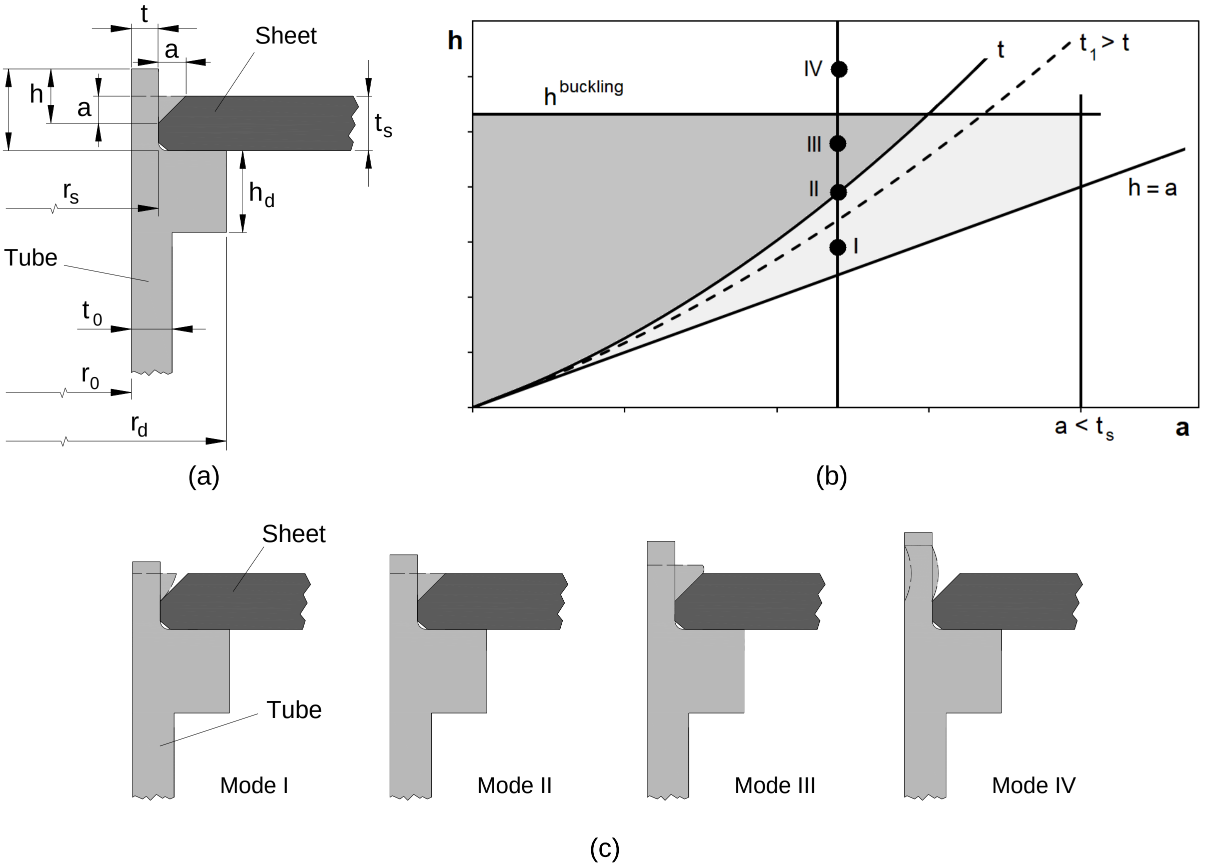


Fig. 3 - Design of the new proposed joint.
(a) Main variables and notation;
(b) Process window as a function of the workability limits associated to the geometry of the bevelled holes and to plastic instability (buckling) of thin-walled rings;
(c) Schematic representation of the plastic deformation modes associated to the different regions of the process window (refer to the deformation modes labelled from I to IV in (b)).

The analytical framework is built upon basic concepts of volume incompressibility derived from the geometries of the bevelled sheet holes and of the free tube ends and additional concepts related to plastic instability (buckling) or cracking during the upsetting of the free tube ends.

Under these circumstances, and assuming that the sheet behaves as a rigid object during the upsetting of the tube end, volume incompressibility determines that the free height h of the tube end to completely fill a bevelled hole with 45º degree inclination is given by,

$$h = a + \frac{a^2\left(a + 3\left(r_0 + t\right)\right)}{3t\left(2r_0 + t\right)} \quad (1)$$

Different thicknesses t of the tube end will give rise to different curved lines (e.g. refer to the dashed curved line labelled as t_1 in Fig. 3b). Each curved line provides the design guidelines to guarantee that the bevelled sheet hole is completely filled by the free tube end without a protrusion above the surface of the sheet.

The workability limit given by the horizontal line of Fig. 3b derives from the minimum height for the occurrence of plastic instability (buckling) of the free tube end,

$$h = h^{buckling} \tag{2}$$

Whereas the workability limit given by the vertical line and inclined lines of Fig. 3b are related to the geometry of the bevelled hole. The workability limit associated to the vertical line of Fig. 3b,

$$a = t_s \tag{3}$$

corresponds to the limiting condition of the side length a of the triangular cross section of the bevelled hole being equal to the sheet thickness t_s .The workability limit associated to the inclined line of Fig. 3b,

$$h=a \tag{4}$$

corresponds to the limiting condition of the free height h of the tube end being equal to the side length a of the triangular cross section of the bevelled hole. In other words, equation (4) corresponds to a situation in which the tube end is co-planar with the sheet surface. It is not possible to work below this line.

Under these circumstances by choosing process variables in different locations of the window chart of Fig. 3b it is possible to obtain the plastic deformation modes (labelled from 'I' to 'IV') that are schematically depicted in Fig. 3c.

Experimentation

The investigation was performed in aluminum AA6063-T6 tubes with an inner radius $r_0 = 14.5$ mm and a wall thickness $t_0 = 1.5$ mm and aluminum AA5754-H111 sheets with a thickness $t_s = 3$ mm. Both materials were utilized in the 'as-supplied' condition.

The mechanical characterization of the tube and sheet materials was performed by means of tensile and stack compression tests and the resulting stress-strain curves are shown in Fig. 4. Further information on the procedure utilized for the mechanical characterization of the tube and sheet materials is available in Alves et al. (2017).

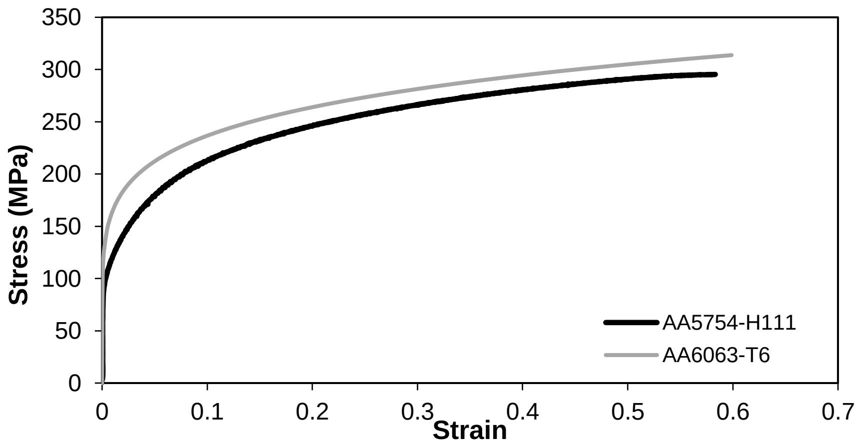


Fig.4 - True stress-true strain curves of the two aluminum alloys utilized in the investigation.

The experimental work plan on the new joining by forming process involved two different sets of tests. The first set of tests was focused on plastic instability (buckling) of thin-walled rings under axial compression loading with the purpose of determining the maximum height of the tube end $h = h_{buckling}$ beyond which buckling is likely to occur. The tests were carried out by compressing different ring specimens with four different wall thicknesses t and six different heights h between flat parallel platens (Table 1).

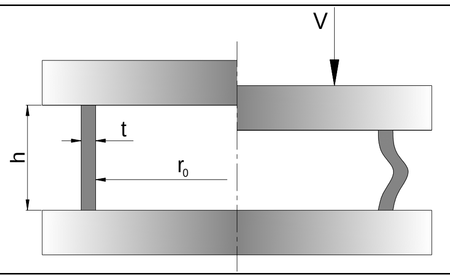
r_0 (mm)	
14.5	
h (mm)	
2 to 6	
t (mm)	
0.75, 1.0, 1.25, 1.5	

Table 1 - Experimental work plan for determining the occurrence of plastic instability (buckling) in the upset compression of thin-walled rings.

The second set of tests was focused on the new proposed variant of the joining by forming process. The tests were performed with the same laboratory tooling system that had been previously developed for the joining of tubes to sheets with bevelled holes (refer to Fig. 2) and the experimental work plan is briefly summarized in Table 2 and Table 3. The designation of the test cases is made in accordance to Fig. 3.

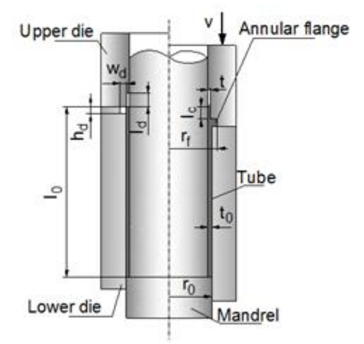
r_0 (mm)	t_0 (mm)	h_d (mm)	w_d (mm)	t (mm)	l_d (mm)	
16	1.5	3 to 4	1 to 2.75	0.75 to 1.0	2.5 to 12	

Table 2 - Typical range of process parameters utilized in the experiments for boss forming the tubes (nomenclature according to Figure on the right).

Test case	Tube				Sheet			
	r_o (mm)	t_0 (mm)	h (mm)	t (mm)	r_s (mm)	t_s (mm)	a (mm)	
1			2.0	1.25			1.5	
2			2.4	1.25			1.5	
3	14.5	1.5	3.0	1.25	15.75	3	1.5	
4			4.0	1.25			1.5	

Table 3 - Summary of the experimental work plan for joining tubes to sheets with bevelled holes by sheet-bulk forming and upsetting and photographs of tubes before and after boss forming, as well as two views of the final result produced by the new proposed joining process.

The results of the first and second set of tests will be subsequently utilized to setup the process curve $h = f(a, r_0, t)$ for sheet-bulk formed tubes with $r_0 = 14.5$ mm, $t = 1.2$ mm and $h = h^{buckling}$ and to validate the theoretical framework against numerical and experimental data.

Finally, the third set of tests consisted of destructive tests aimed at determining the maximum force that the new proposed joint is capable to withstand without failure.

Finite Element Modelling

The numerical modelling of the joining by forming of tubes to sheets with bevelled holes was carried out with the in-house finite element computer program I-FORM (Nielsen et al., 2013). The models made use of the rotational symmetry conditions of the process and discretized the longitudinal cross-section of the tubes and sheets by means of quadrilateral elements. The tubes and sheets were modelled as deformable objects and contact with friction along their interfaces was solved by means of a two-pass node-to-surface algorithm with penalization of the normal gap velocities in order to avoid penetration. The tool parts were modelled as rigid objects and their geometries were discretized by means of linear contact-friction elements.

Fig. 5 shows the initial and final finite element meshes in the mechanical interlocking by upsetting of the free tube end against the sheet. The overall central processing unit (CPU) time for a typical analysis such as this one was approximately equal to 10 min. on a computer equipped with one Intel i7 CPU.

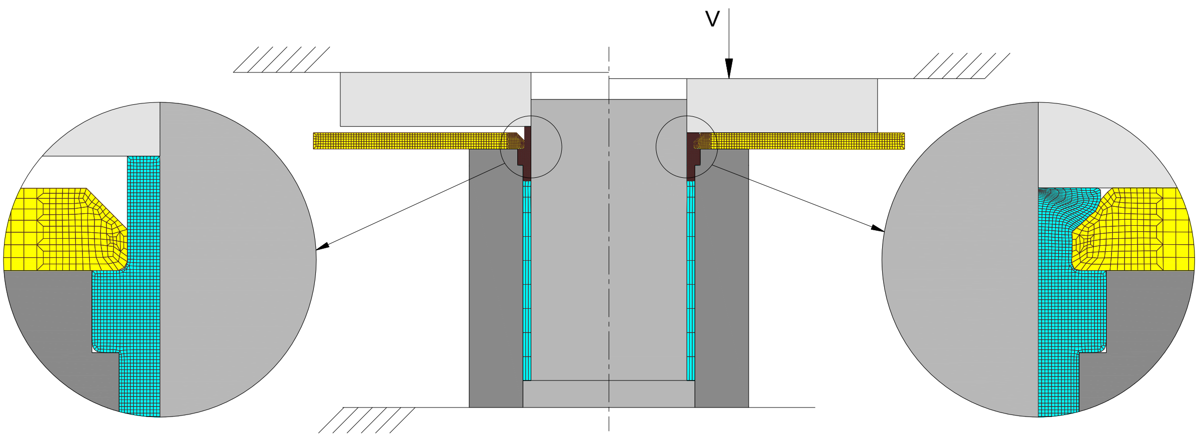


Fig. 5 - Finite element modelling of the second stage (mechanical interlocking) of the proposed joining by forming of tubes to sheets with bevelled holes at the initial and final instants.

Results and Discussion

Fig. 6 provides a photograph of the thin-walled ring with $t = 1.5$ mm thickness and different heights h before and after upsetting between flat parallel platens: The enclosed table summarizes the values of the critical heights $h_{buckling}$ above which the rings will fail by plastic instability (buckling).

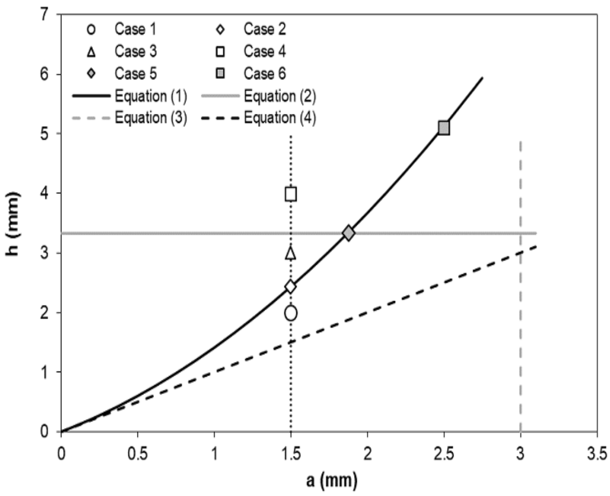
The analytical framework is built upon basic concepts of volume incompressibility derived from the geometries of the bevelled sheet holes and of the free tube ends and additional concepts related to plastic instability (buckling) or cracking during the upsetting of the free tube ends.

t (mm)	$h_{buckling}$ (mm)
0.75	2
1.00	3
1.25	3~4
1.50	4

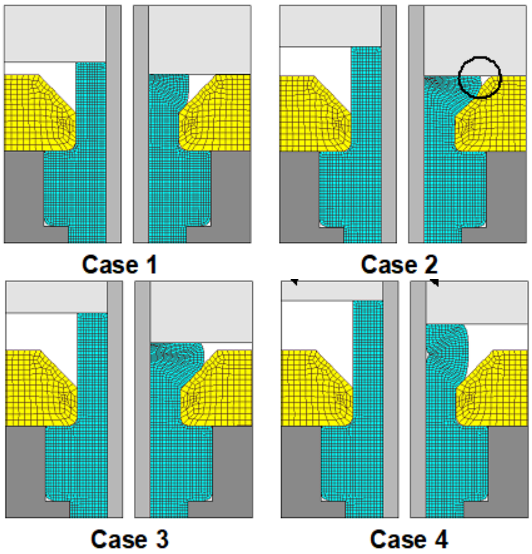
(a) (b)

Fig. 6 - Upset compression of thin-walled rings between flat parallel platens.
(a) Photographs of the thin-walled rings before and after compression.
(b) Critical heights $h_{buckling}$ for the occurrence of plastic instability for rings with different thicknesses.

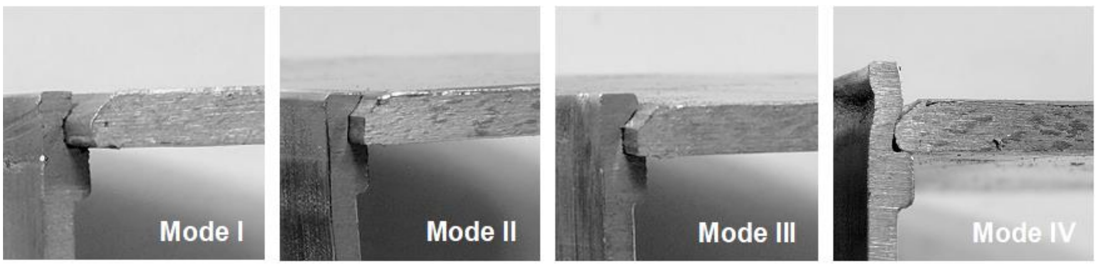
The results obtained with this first set of tests allowed to determine the volume of the material in the mechanical interlocking between the tube and sheet by choosing values of the free height h of the tube end slightly larger than that given by equation (1) of the analytical model (refer to the curved line of Fig. 7a), due to the plastic deformation of the bevelled holes (not considered by the equation (1)) that leads to an increase of the side length a.



(a)



(b)



(c)

Fig. 7 - Joining a tube to a sheet by enhanced boss forming and upsetting.
(a) Process window for selecting the free height h of a tube end with a wall thickness $t = 1.25$ mm as a function of the side length a of the triangular cross section of the bevelled hole;
(b) Finite element predicted cross sections of the joints corresponding to deformation modes I to IV (Cases 1 to 4 of Table 3) before and after upsetting the free tube ends against the bevelled holes of the sheets;
(c) Photographs of joints corresponding to deformation modes I to IV shown in (b).

The analysis of Fig. 7 allows concluding that there is a very good agreement between the analytical procedure, the finite element numerical estimates and the experimental results for the test cases 1 to 4 of Table 2, were the cases 1 to 4 were produced under deformation modes I, II, III and IV.

Deformation mode I corresponds to an inadmissible joint that is not completely filled due to a significant lack of upset material from the tube end. In contrast, deformation mode III corresponds to a joint with a protrusion above the surface of the sheet caused by excess of upset material. This joint may be acceptable if the protrusion causes no problem to its utilization in service but it is worth mentioning that the maximum size of the protrusion is also limited because slender tube ends will fail by plastic instability (buckling) during upset compression and will give rise to an inadmissible joint (deformation mode IV).

Deformation mode II, characterized by sound joints with completely filled volumes and no protrusions of the upset tube ends above the surface of the sheets should correspond to process variables taken from the portion of the curved line of Fig. 7a (equation (1)) placed below the workability limit $h = h^{buckling}$ (refer to Cases 2 and 5).

Fig. 8 shows the experimental and finite element predicted evolution of the force with displacement for two different annular flanges (on the left side) and for the upset compression forces with displacement for deformation modes II and IV of Fig. 7b.

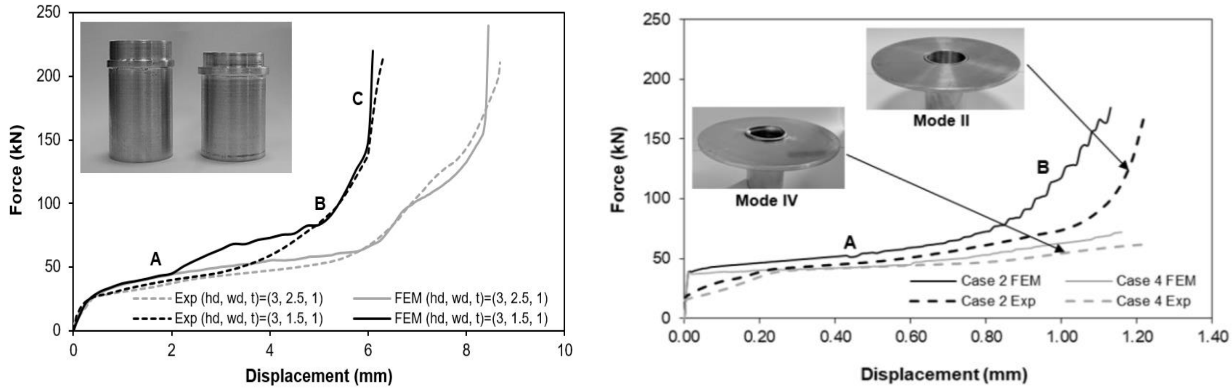


Fig. 8 - Experimental and finite element predicted force-displacement curves for the boss forming of the tubes (left hand side) and for cases 2 and 4 of Table 2 during the second stage (mechanical interlocking) of the joining of a sheet-bulk formed tube to a sheet with a bevelled hole (right hand side).

As seen, both curves compare well and allow identifying two different patterns when attempting to join tubes to sheets by means of the new proposed process.

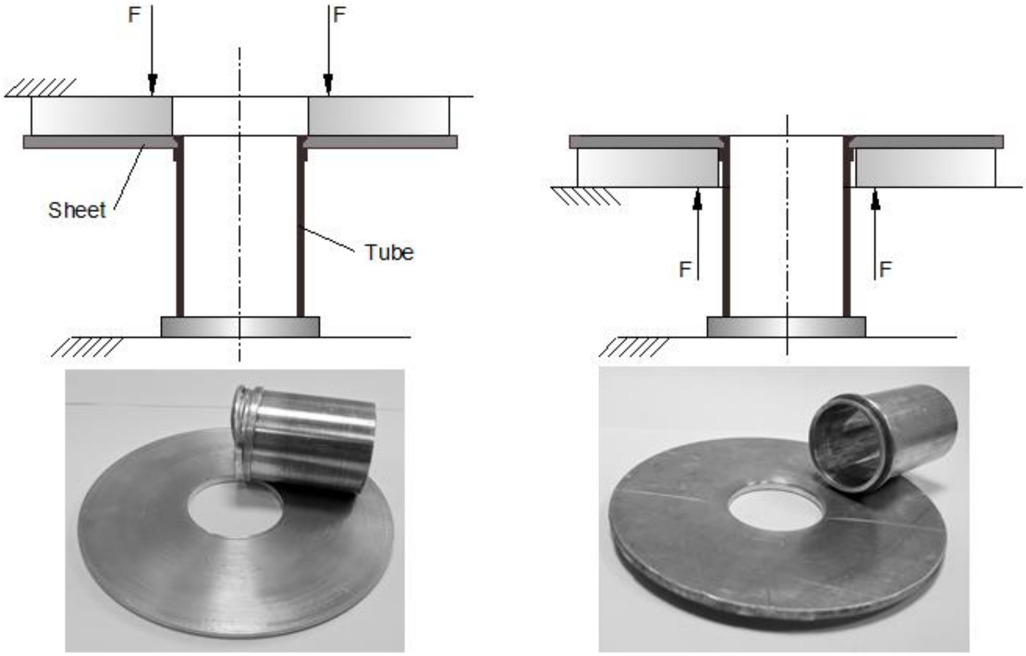
Deformation mode II show a monotonic growth of the force as the tube end is progressively upset by compression along the axial (longitudinal) direction (region labelled as ‘A’) followed by a steep rise corresponding to the mechanical lock during which the tube end fills the bevelled hole of the sheet (region labelled as ‘B’).

The experimental and finite element curves corresponding to deformation mode IV only reveal a slight monotonic growth of the force with displacement (refer to the solid and dashed grey lines of Fig. 8). Their overall level of magnitude is smaller than that of deformation mode II due to the development of local buckling at the tube end.

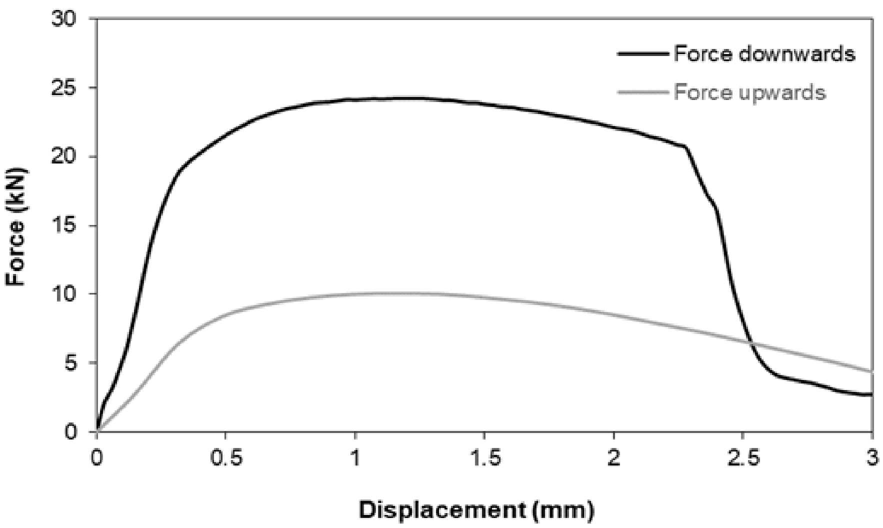
To finalize is important to evaluate the performance of the new proposed joint by means of destructive tests aimed at detaching the sheet from the tube end. Fig. 9a shows a schematic representation of the two experimental setups that were utilized to perform the destructive tests and Fig. 9b shows the corresponding force-displacement curves.

The tests were performed for case 2 of Table 3 (deformation mode II) with the forces applied downwards and upwards. Results show that the new joint is capable of withstanding 24 kN of downward force and 10 kN of upward force before failure. In case of the destructive testing with downward force, failure takes place by cutting off the sheet material located below the triangular cross section of the bevelled hole along the inner straight edges of the tube flange, which act as a cutting die due to previous strain hardening. In case of the destructive testing with downward force, failure takes place by bending and drawing of the upset tube end through the inner radius of the bevelled sheet hole.

However, both values of destructive force are considerably larger than that obtained for the previous solution (4 kN) by Alves et al. (2017), in which the mechanical locking between the tube and sheet was obtained by curling the tube ends outwards instead of upsetting.



(a)



(b)

Fig. 9 - Destructive pull-out tests of a joint without protrusion of the upset material above the sheet surface (Case 2 of Table 3).

(a) Schematic representation of the two experimental setups (force applied downwards and upwards) with pictures of the joints after being tested;

(b) Experimental evolutions of the force with displacement for the two experimental setups.

Conclusions

Joining by forming of sheets to tubes at room temperature can be successfully accomplished by combining partial sheet-bulk of the tube wall thickness and upsetting of the free tube end against a flat-bottomed sheet hole. Enhanced boss forming by partial compression of the tube wall thickness along the longitudinal direction allows material to be piled-up into large and robust annular flanges with tight dimensional control. Upsetting of the free tube end against a sheet with a bevelled hole produces a mechanical lock that is capable of withstanding forces up to 10 kN (for the tested samples) and of eliminating the protrusion of the tube end above the sheet surface. The proposed joining by forming process can however be used with longer than necessary boss-formed tube ends in case a small bump of upset tube material is required above the sheet surface. Nevertheless, there is a limit to this length due to the occurrence of local buckling, in case of very slender tube ends.

The analytical model for designing the joints proved to be effective and its validation against finite element predictions and experimental observations revealed minor discrepancies that are attributed to the bevelled hole being considered a rigid object during the upsetting of the tube end.

To conclude, it is worth mentioning that the new proposed joining by forming process allows fixing tubes to sheets made from dissimilar materials, avoids the utilization of addition materials or adhesives and it is relatively easy to disassembly at the end of live, allowing recyclability of the tubes and sheets.

Acknowledgments

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