

A New Deformation-Assisted Joining Process for Fixing Sheets to Tubes

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Abstract: This dissertation proposes a new concept for a joining by forming process for joining sheets to tubes away from the tube's end. The sheet-tube connection is obtained by squeezing the sheet adjacent to the outer tube radius, instead of applying direct loading on the tube itself as it was done before in the previous joining by forming processes. The development compares both experimental and finite element modelling results in order to identify the main operating parameters. A deep understanding of their influence in plastic flow allows to characterize the different modes of deformation leading to acceptable and unacceptable joints. Utilization of a deformation-zone geometry parameter to characterize plastic flow inside sheet thickness leads to the conclusion that combination of inhomogeneous and homogeneous deformation through the squeezing depth is necessary for obtaining sound joints with good pull-out destructive forces. Further investigation regarding the influence of the squeezing depth on the joint's performance and the interdependence between the main parameters will allow for the validation of the concept. Moreover, further investigation was made in relation to the new surface formation mechanism, the forces involved in the process and some characteristic behaviours found in this new technique such as the excessive sheet bending.

Introduction

In the production of every structure, joining of a certain number of components is necessary. Tubes and sheets don't live alone and are usually combined for producing improved products or structures. Looking to today's context, it's evident that in order to join components, the most used techniques relate to either mechanical fasteners, adhesive bonding or welding technologies (Fig.1). However, these two conventional techniques bring certain problems, mainly in areas related to environmental impacts and structural performance, for example, the use of mechanical fasteners adds a lot of weight to structures.

In a study performed by the company Trumpf [1] the environmental impact of the use of welding technologies was studied having in consideration factors such as: impact on the ozone layer through photochemical reactions between ozone and welding gases, acidification potential among other harming effects. Most common welding techniques are known to be responsible for an enormous amount of pollution and potential global warming effects. Moreover, another widely used technique is adhesive bonding but this technology has the main limitation of depending on a very thorough surface cleaning and usually have long cure times.

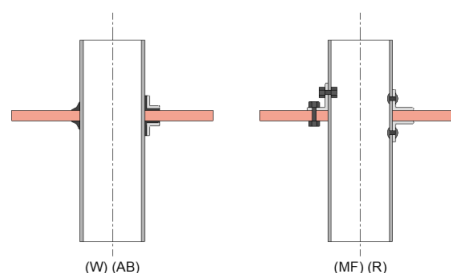


Fig. 1. Sheet-tube connections obtained by welding (W), adhesive bonding (AB), mechanical fastening (MF) and riveting (R) in the tube away from its end.

Joining by forming [3] had as its first application the connection of tubes to sheets at room temperature, in 2011 and published by Alves et al. [2] (Fig. 2). The process was based on the combination of compression

beading and tube inversion, requiring no additional filler materials and accessories. This avoided the problems of forces being concentrated at the points of fastening or riveting. However, using the compression beading technology might lead to the resulting tube sheet connections showing 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. More recently, Alves et al. presented new deformation-assisted processes to secure connections between components, designated as Sheet-Bulk Forming and Boss Forming [4,5] that based their nature on forming an annular flange by tube compression. This annular flange would then be used as support for the other component to be joined. These two processes were usually combined with flaring operations, that are essentially tube inversions [6]. These new processes (Fig. 2). are part of a new field of study designated as Joining by Forming. Despite the many advantages of these new joining processes, two main problems still arise:

- Most techniques still require multiple separate operations, which in turn increases lead times and difficults the industrial application of these new technologies.
- The techniques that were developed to be successful in a single operation, cannot be used in materials with low fracture toughness, which limits the applicability and industrial integration of these processes.

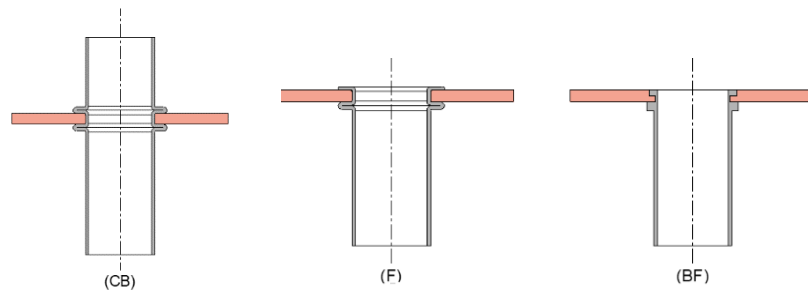


Fig. 2. Sheet-tube connections obtained by Compression Beading (CB), flaring with compression beading (F) and boss forming (BF) of the tube end.

Process Description, Main Parameters and Relevant Considerations

The process looks at joining by forming in a different perspective than has been done so far, and connects the sheet to the tube by squeezing the sheet adjacent to the outer tube radius, instead of applying direct loading on the tube itself. As seen in Fig. 3, the goal is to locally compress the sheet up to a predefined depth in order to shape an inner tube bead and fix the sheet to the tube by mechanical interlocking.

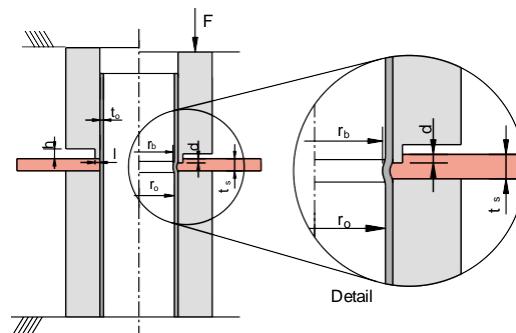


Fig. 3. Schematic representation of the tool system utilized for joining sheets to tubes by annular sheet squeezing, at the open and close positions.

The dissertation focused on identifying the major operating parameters and understanding their influence in material flow and failure. After experimental and numerical developments it was possible to set as main parameters the cross-section recess-length (l) and the squeezing depth (d), both represented in Fig.3. The research work starts by studying the physics behind separation of material at the cross-section recess

corner of the punch when the depth of squeezing d is large and assesses whether the new surface is formed by shear or not [7]. Afterwards, the shear forces are looked into and answers are given to whether the required force (and energy) to form the new surface is a small or large percentage of the total force (and energy) required to squeeze the sheet thickness adjacent to the outer tube radius.

Afterwards, the works continues by isolating the major process variables to study and understand their influence on the deformation modes which led to admissible and inadmissible joints. In a first stage, different cross-section recess lengths were tested, and the squeezing depth was kept constant. In this case, three modes of deformation are characterized, and a distinction is made between acceptable and unacceptable joints resulting from different plastic deformation-zone geometries [8]. In a later stage, the study was focused on analysing the strength of the mechanical joint for different values of squeezing depth and keeping the cross-section recess length constant. This methodology allowed to have a common reference base throughout the investigation for analysing material flow resulting from the changes in both variables at the same time and proved the existence of an interdependence between both cross-section recess length and squeezing depth [9]. Further studies were made to the addition of angular inclines to both the contact face and lateral face of the squeezing punch (Fig. 4), showing that there no is advantage in using either one of them. The discussion is supported by experimentation and finite element modelling, and the overall performance of the new proposed joining by forming process is evaluated by means of destructive pull-out tests.

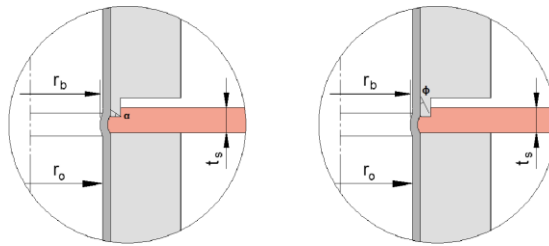


Fig. 4. Schematic representation of the angular inclines given to the squeezing punch's contact face (left) and lateral face (right).

Experimentation

The investigation was performed in aluminum AA6063-T6 tubes with an inner radius r_o 14.5 mm and a wall thickness t_o of 1.5 mm and aluminum AA5754-H111 sheets with a thickness t_s of 5 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. 5.

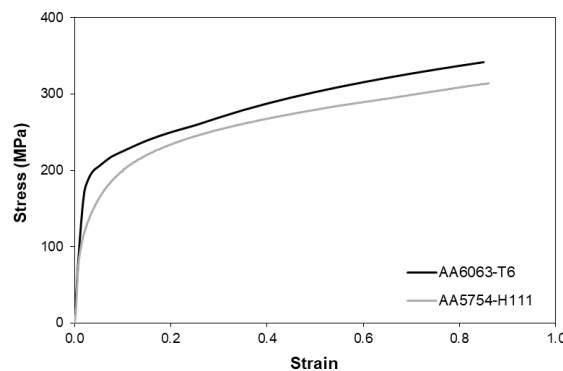


Fig.5. Flow curves of the two aluminum alloys utilized in the experiments.

The experimental work plan on the new joining by forming process involved four different sets of tests (Fig.6).

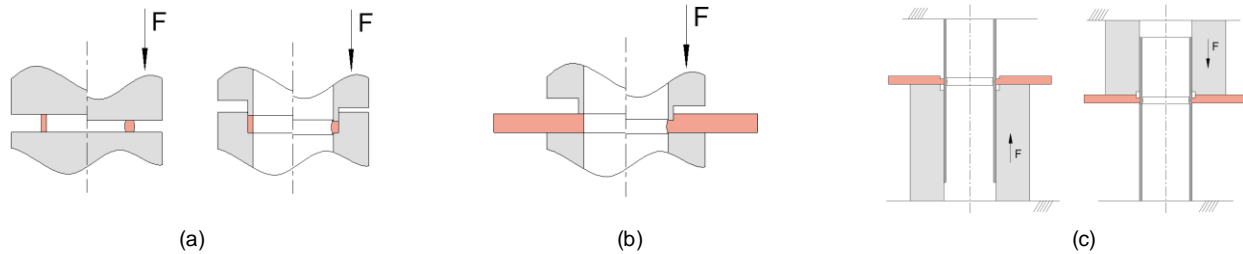


Fig.6. Experimental test types: (a)– Test Type I, Upset Compression of Rings; (b) – Test Type II, Annular Sheet Squeezing; (c) – Test Type IV, Destructive Pull-Out Test.

Experimental tests of Type I consisted of upset compression of rings using in some cases an outward constraint feature and in other cases not. They were of paramount importance in order to understand the physics behind the formation of new surfaces. The experimental development of this type of test is shown in Tab. 1. Tests of Type II were designated as Annular Sheet Squeezing tests and were identical to the Type III tests (Fig. 3) with the sole difference of being performed on standalone sheets instead of the complete tube-sheet setup. Type II tests were essential to understand the shear stress influence in energy required by the process and is represented in Tab. 2 whereas Type III tests were performed in order to understand the influence of the main parameters that govern the process (cross-section recess length, squeezing depth) are represented in Tab. 3 and the experimental development of tests to the squeezing punch's contact face angular incline are represented in Tab. 4. Tests of Type IV consisted in destructive pull-out tests to evaluate the maximum force that the new sheet-tube joints are capable to withstand before failing. There are two types of setup used for this test that are shown in Fig. 6.

Test Case	r_0 (mm)	t_0 (mm)	t_s (mm)	l (mm)	h (mm)	d (mm)
Upset Compression of Rings without Outward Constraint						
1R	14.5	-	5	1.8	-	2
2R				2		
Upset Compression of Rings with Outward Constraint						
1RC	14.5	-	5	1.8	-	2
2RC				2		

Tab. 1. Work plan for upset compression of aluminium rings, for the different constraint situations.

Test Case	r_0 (mm)	t_0 (mm)	t_s (mm)	l (mm)	h (mm)	d (mm)
1S	14.5	-	5	1	-	2
2S				1.5		
3S				1.8		
4S				2		

Tab. 2. Work plan for the Annular Sheet Squeezing tests.

Test Case	r_0 (mm)	t_0 (mm)	t_s (mm)	l (mm)	h (mm)	d (mm)
1	14.5	1.5	5	0.5	2	2
2				1		
3				1.5		
4				2		
5				2.5		
6				3		
7				5		
8	14.5	1.5	5	2	4.7	1
9						2
10						3
11						3.5
12						4

Tab. 3. Work plan for the study of the influence of the cross-section recess length and the squeezing depth.

Test Case	r_0 (mm)	t_0 (mm)	t_s (mm)	l (mm)	h (mm)	α (°)	d (mm)
13	14.5	1.5	5	2	4.7	15	2
14							2.5
15							3
16						30	2
17							3

Tab. 4. Work plan for the study of the influence of the angular incline in the contact surface of the squeezing

Finite Element Modelling

The numerical modelling of the joining by forming of tubes to sheets through annular sheet squeezing was carried out with the in-house finite element computer program I-FORM 2d. The tubes and sheets were modelled as deformable objects and the dies were modelled as rigid objects. The friction factor between material and die was set to 0.1 and the friction factor between materials was defined as equal to 0.5. Fig. 7 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 varied between 60 and 100 min on a computer equipped with one Intel i7 CPU.

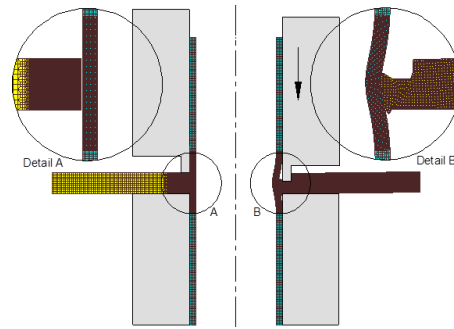


Fig. 7. Initial and Final FEM model for Case 4.

Results and Discussion

Physics of the New Surface Formation Mechanism

The photographs in Figure 8 show the different morphologies that can be observed in section ST (refer to Fig. 8 (f)) resulting from the annular squeezing of a sheet with an inner hole. The first three zones labelled as 'A', 'B' and 'C' show signs of severe damage by adhesive and abrasive wear originated from the relative motion between the contacting surfaces of the punch and sheet. The adhesion to the squeezing punch happens through cold welding and is then dragged along the surface, severely wearing the surface, eliminating any evidence of shear behaviour. Zone D (Fig. 8 (e)) is not characteristic of annular squeezing of sheets with inner holes. In fact, this 'region' resulted from separation of the squeezed sheet material from section ST after finishing the test. The separation was done by bending and this explains the reason why the SEM image included in Fig. 8 (e) reveals circular dimpled structures typical of material separation by tension.

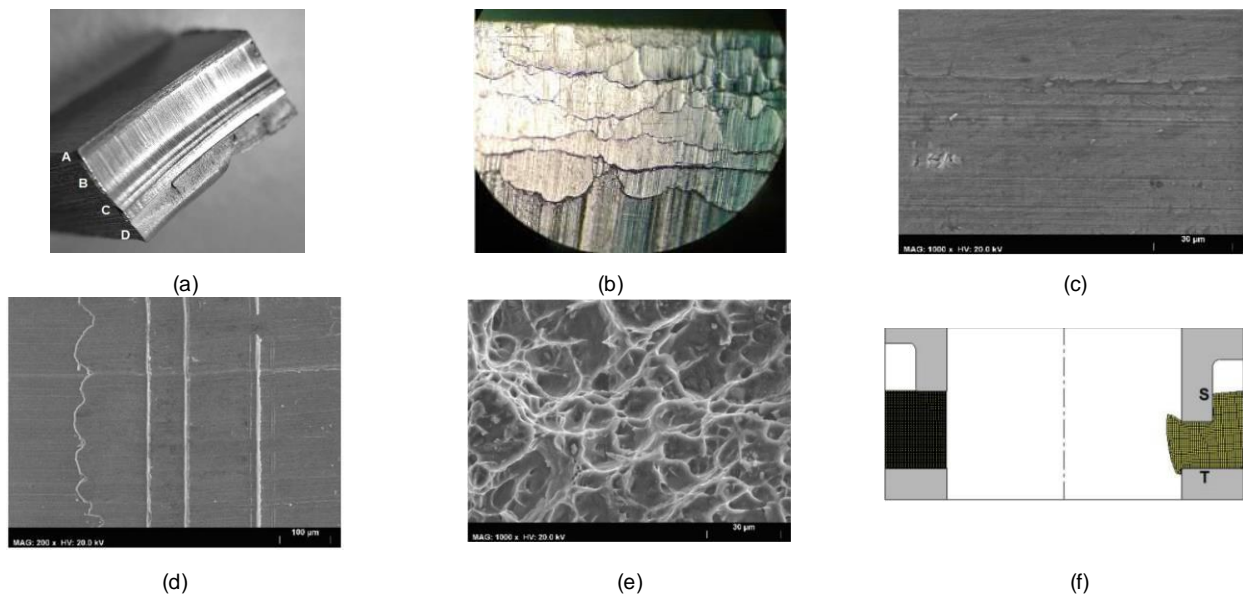


Fig. 8. Photographs of the different morphologies of the surface in section ST: (a) – Schematic representation of the four different zones; (b) – Zone A (Adhesion); (c) – Zone B (Penetration); (d) – Zone C (Transition); (e)– Zone D (Tension Separation); (f) - Initial and final cross-section computed meshes for different squeezing depth d values.

The experimental force-displacement evolutions for the upset compression of rings and annular sheet squeezing tests (Fig. 10) give an interesting result. As seen, the evolution of the free upset ring compression (Case 4R) is similar to that of the annular squeezing of a sheet with an inner hole (Case 4S),

allowing us to conclude that the force and energy required for annular sheet squeezing is overwhelmingly due to plasticity and friction. In other words, the force and energy required for material separation and formation of a new surface along a typical section ST is negligible.

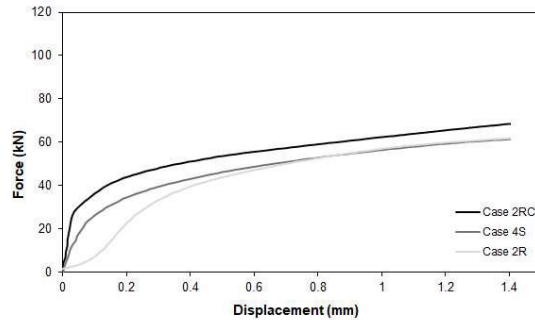
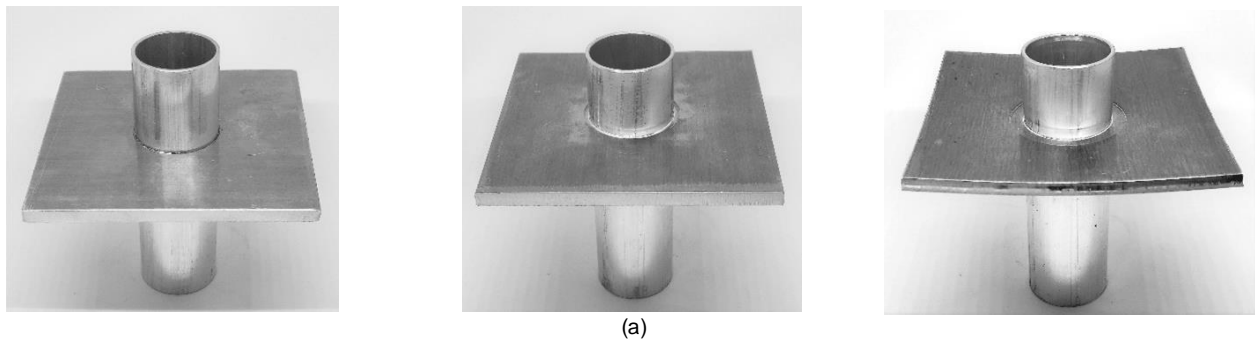


Fig. 10. Experimental force-displacement evolutions for cases 2RC, 4S and 2R of Tab. 1.

Influence of the Cross-Section Recess Length

Experimental observations and finite element simulation of the entire set of test cases listed in Tab. 3 allowed identifying three different modes of deformation (Fig. 11). Main differences between these modes results from material flow in the sheet thickness and can be quantified by a single deformation-zone parameter $\Delta = t_s / l$ defined as the ratio of the sheet thickness t_s to the cross-section recess length l .

In fact, as seen in the finite element computed distribution of effective strain rate for $\Delta = 10$ (case 1 in Fig. 11 (b)), plastic deformation is localized near the cross-section recess without ever extending through the thickness of the sheet. The deformation mode associated to large values of Δ will be hereafter designated as 'mode I' and is not appropriate for sheet-tube connections because of the above-mentioned reasons. In contrast, finite element predicted distribution of effective strain rate for $\Delta = 1$ (case 7 in Fig. 11 (b)) shows that plastic deformation extends through sheet thickness from the beginning of punch squeezing. This means that the overall volume of squeezed material is large and, therefore, less constricted from flowing outwardly by adjacent material. Excessive bending of the sheet will occur as a result of non-symmetric material flow caused by the fact that the squeezing punch moves from top-to-bottom while the lower die is stationary (case 7 in Figs. 11 (a)). For this reason, the deformation mode associated to $\Delta = 1$, which will be hereafter designated as mode III, is also not adequate for sheet-tube connections. The explanations associated to modes I and III, allow concluding that appropriate values of Δ must entail a combination of inhomogeneous and homogeneous deformation during punch squeezing (case 4 in Fig. 11 (b)). This will give rise to near symmetrical sheet-tube contact interfaces, good amount of material squeezed against the tube and enough constriction from the external rigid zones of the sheet to prevent material from flowing outwardly and bending. This mode of deformation was found to be optimal as it also resulted in the largest inner tube beads (Fig. 12) and will hereafter be designated as Mode II.



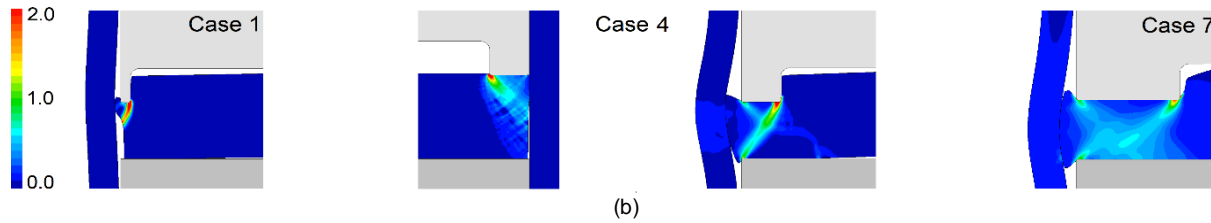


Fig. 11. Typical modes of deformation in the joining of sheets to tubes by annular sheet squeezing: (a) - Photographs of sheet-tube connections for cases 1, 4 and 7 of Tab. 3; (b) - Finite element predicted distribution of effective strain rate (s^{-1}) for the sheet-tube connections shown in (a).

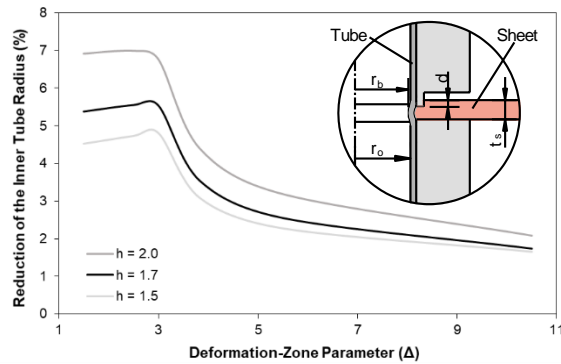


Fig. 12. Finite element predicted reduction of the inner tube radius as a function of the deformation-zone parameter Δ for different maximum depths of squeezing d . The enclosed scheme shows a detail of the tube joint with appropriate notation.

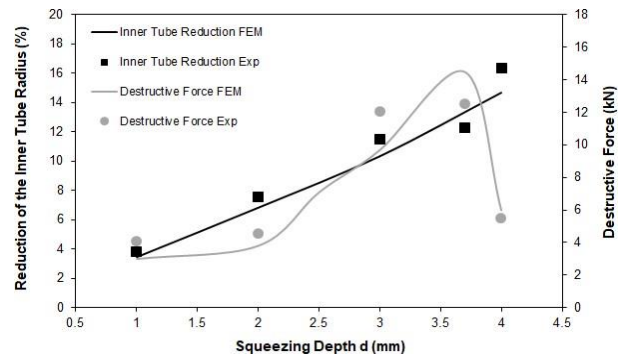


Fig. 13. Influence of the squeezing depth d on the quality and strength of the sheet-tube connections.

Influence of the Squeezing Depth

Having performed the destructive pull-out tests for all the test cases listed in Tab. 3 it is now possible to combine, in a single graphic, the influence of the total squeezing depth on the reduction $R = (r_o - r_b)/r_b$ of the inner tube radius and on the maximum destructive pullout force. The result is shown in Fig. 13 and allows concluding that the squeezing depth d should not be selected as large as possible to obtain the maximum reduction of the inner tube and the best mechanical interlock. This is because, large squeezing depth values d will inevitably lead to small sheet thicknesses below the cross-section recess corner of the punch and, therefore, to pull-out failure by shearing under small values of force.

Cross-Section Recess Length and Squeezing Depth Interdependence

The neutral region is defined as the separation between inward flow of material that goes towards the tube and outward flow, and where the flow velocity is null. By plotting the radial velocity for different squeezing depths (Fig. 6), a change in the position of the neutral region can be observed for variations of the two main variables l and d , that will impact the relation between the optimal cross-section recess length and the optimal squeezing depth. This change in the position of the neutral region will cause different material flows in different directions as it can be seen by the numerical simulations of Fig. 14.

What's interesting to see is that the finite element results of the radial flow velocity for different values of both the cross-section recess length and the squeezing depth allow to conclude that different optimal solutions can be achieved depending on the specifications of the materials and tools used.

The relationship between the reduction of the inner tube radius, the cross-section recess length and the squeezing depth plotted in Fig. 15, shows that the optimal cross-section recess length decreases as the squeezing depths increases.

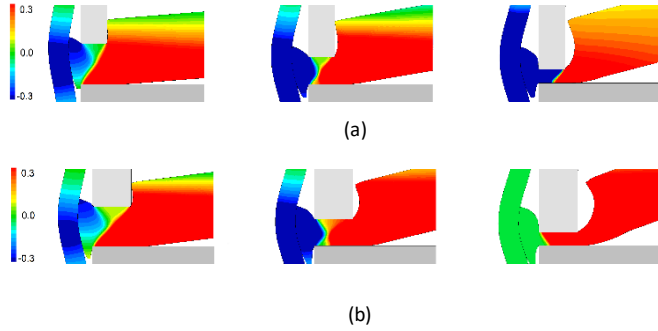


Fig. 14. Radial flow velocities for different squeezing depths d for each cross-section recess-length l : (a) – Case 4 of Tab. 3; (b) – Case 6 of Tab. 3

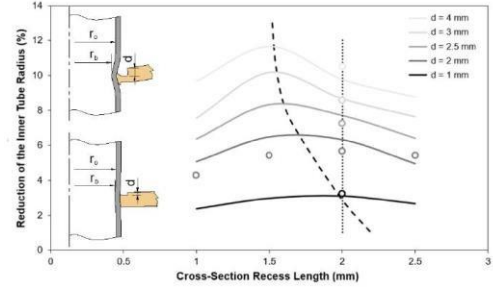


Fig. 15. Reduction of the inner tube radius for different squeezing depths for each cross-section recess lengths of Table 1.

Process' Forces and Pressures

The total force to fabricate a sheet-tube connection by the new joining by forming process may be decomposed into two terms, $F = F_{sq} + F_{ib}$, where, F_{sq} is the force to perform the annular squeezing of standalone sheets and F_{ib} is the force to shape the inner tube beads. The evolutions labelled as '2S' and '4S' in Fig. 16 correspond to the experimental and finite element predicted values of for the annular squeezing of standalone sheets with the punches that were used in cases 2 and 4 of Tab. 2. As seen, the agreement is good and allows identifying a typical pattern of bulk forming with a steep force increase at the beginning followed by a moderate force growth until the maximum squeezing depth d . This result enables classifying the process as belonging to the new class of forming processes that is nowadays designated as 'sheet-bulk forming'.

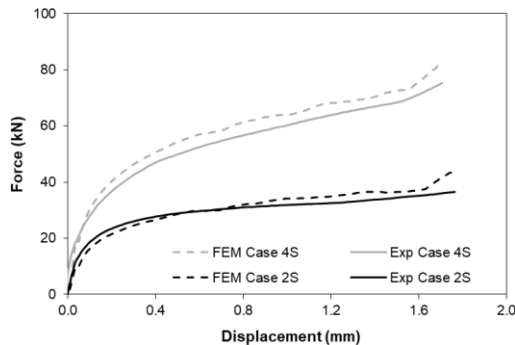


Fig. 16. Experimental and finite element predicted force-displacement evolutions of annular squeezing of standalone sheets with the punches used in cases 2 (2S) and 4 (4S) of Tab. 2.

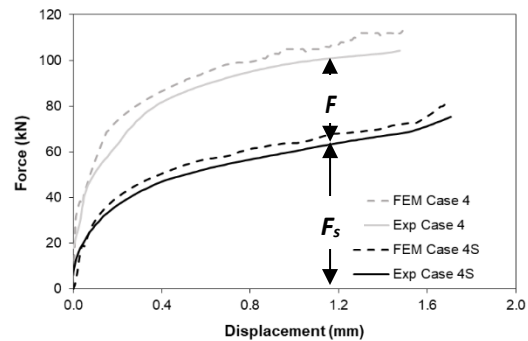


Fig. 17. Experimental and finite element predicted force-displacement evolutions of annular squeezing of standalone sheets with the punches used in cases 2 (2S) and 4 (4S) of Tab. 2.

Now, considering the force-displacement evolution to fabricate the sheet-tube connection corresponding to case 4 of Tab. 3 (mode II) depicted in Fig. 17, one may conclude that the force F_{sq} that is needed to perform the annular squeezing of the standalone sheet accounts for nearly 62% of the total force F . The remaining 38% corresponds to the force F_{ib} that is needed to shape the inner tube bead and obtain the sheet-tube connection by mechanical interlocking. Fig. 18 shows the maximum experimental and finite element computed pressure p_{max} as a function of the deformation-zone parameter Δ . As seen, the agreement is good, and the maximum pressure increases with up to a value of approximately 700 MPa for $\Delta = 10$. This increase is due to redundant deformation which becomes much more important as plastic flow changes from homogenous ($\Delta = 1$) to inhomogeneous ($\Delta = 10$).

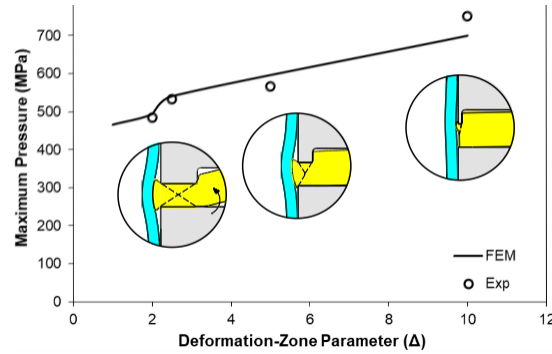


Fig. 18. Experimental and finite element predicted evolution of the maximum pressure p_{\max} with the deformation-zone parameter Δ . Schemes with localized flow surfaces are included for different values of Δ .

Destructive Pull-Out Results and Joint Validation

The destructive pull-out tests were done in two opposite directions and it was initially expected that the joint's behaviour would differ according to the pull-out direction. The results ended up confirming that expectation as both experimental and numerical data showed a different maximum pull-out destructive load depending on the pull-out direction. The results are depicted in Fig. 19.

The destructive pull-out tests showed an interesting feature of the process. The joint destruction force-displacement evolutions had great resemblance with that of an extrusion curve which allowed to conclude that the sheet actually functions as a floating die and the tube is forced to pass through it reducing its inner radius from r_0 to r_b . The load would increase until a peak was reached and from that point on, the load would decrease and reach a stationary behaviour, just like a normal extrusion curve would show.

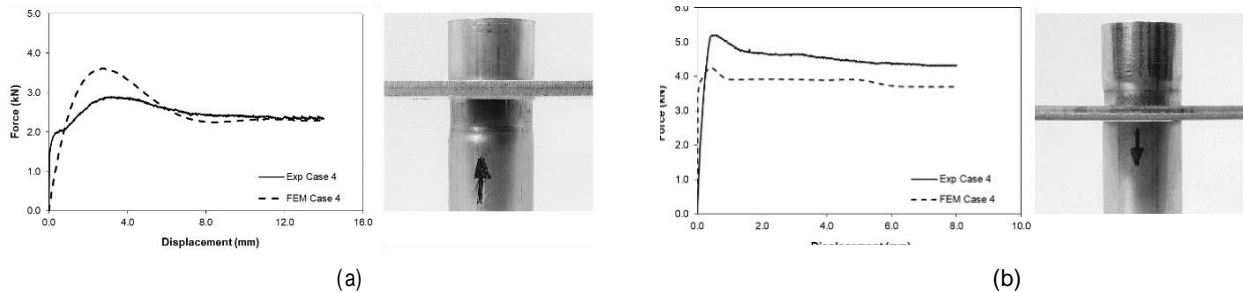


Fig. 19. Experimental and finite element predicted value for the destructive pull-out load in different directions; (a) - Experimental and finite element predicted value for the force-displacement evolutions for the destruction test of Case 4 in the Bottom-Up direction and the respective experimental result photograph; (b) - Experimental and finite element predicted value for the force-displacement evolutions for the destruction test of Case 4 in the Up-Bottom direction and the respective experimental result photograph.

When the squeezing depth is varied, the destructive pull-out tests produce different results. Because the resisting sheet section is very reduced, the risk of rupture is increased, and it becomes necessary to identify a threshold value for the squeezing depth that delimits the transition from a non-rupture to a rupture situation. Observing the results in Fig. 20 for the destructive pull-out test for depths equal to 3.5 mm and 4 mm, it can be concluded that both cases suffered rupture. Nevertheless, it is immediately seen that for cases where the value of the squeezing depth is equal to 4 mm (Case 12), a total rupture of the joint occurs whereas, for depths equal to 3.5 mm (Case 11), the rupture isn't total. This observation allows the setting of a threshold value for the squeezing depth that separates cases where total rupture happens and where partial rupture happens.

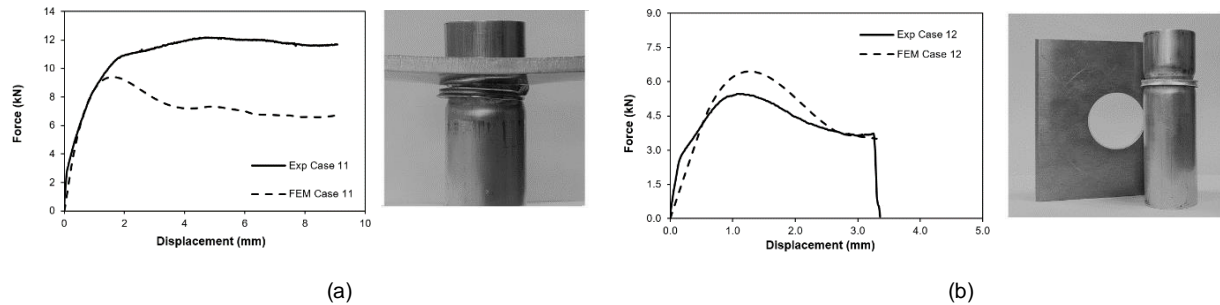


Fig. 20. Experimental and finite element predicted value for the destructive pull-out load in different directions: (a) - Experimental and finite element predicted value for the force-displacement evolutions for the destruction test of Case 11 in the Bottom-Up direction and the respective experimental result photograph; (b) - Experimental and finite element predicted value for the force-displacement evolutions for the destruction test of Case 12 in the Bottom-Up direction and the respective experimental result photograph.

Conclusions

Joining a sheet to a tube away from the tube end can be successfully performed by squeezing the sheet adjacent to the outer tube radius in order to shape an inner tube bead and perform a mechanical interlocking. Fixing a sheet to a tube by annular sheet squeezing involves creation of a new surface by in-plane shear. The surface is formed ahead of the cross-section recess corner of the punch and its morphology mainly consists of grooves parallel to the punch moving direction. The grooves are caused by fragments that detached from the sheet during crack opening (surface formation) and subsequently adhere to the punch by cold welding. Experimentation and finite element modelling proved the feasibility of the new joining by forming process and allowed identifying major operating parameters and their influence in the overall joining procedure. Resort to a deformation-zone parameter, defined as the ratio of the sheet thickness to the cross-section recess length of the punch, to characterize plastic flow inside sheet thickness helped establishing fundamental design guidelines. It was shown that appropriate values of the deformation-zone parameter to obtain sound sheet-tube connections should be in-between limiting values corresponding to inhomogeneous and homogeneous deformation. Full inhomogeneous deformation leads to high pressures and poor mechanical interlocking because the resulting sheet-tube joint is mainly formed upon material adjacent to the cross-section recess length of the squeezing punch. In contrast, full homogeneous plastic deformation provides large volumes of squeezed material that are less constricted from flowing outwardly by the remaining non-deforming sheet material. The sheet squeezing depth influences the quality of the mechanical interlocking and the overall pull-out strength of the resulting sheet-tube connections. Larger depths give rise to larger reductions of the inner tube radius and, therefore, to stronger mechanical interlocks. But larger depths also give rise to abrupt pull-out failure of the sheet-tube connections by shearing under significantly reduced forces. In contrast, smaller depths give rise to sheet-tube connections that fail by means of an extrusion-based mechanism under large pull-out forces.

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